Approach for Estimating Exposures and Incremental Health Effects from Lead due to Renovation, Repair, and Painting Activities in Public and Commercial Buildings

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Acronyms and Abbreviations

Acronym / Abbreviation	Stands For
AERMOD	Atmospheric dispersion modeling system developed by the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) Regulatory Model Improvement Committee (AERMIC)
BWR	Birth Weight Reduction
CBECS	Commercial Building Energy Consumption Survey
CDC	Centers for Disease Control and Prevention
CHAD	Consolidated Human Activity Database
CV	Coefficient of Variation
CVDM	Cardiovascular Disease Mortality
DOE	Department of Energy
EPA	U.S. Environmental Protection Agency
FSIQ	Full Scale Intelligence Quotient
GFR	Glomerular Filtration Rate
GSD	Geometric Standard Deviation
HOME	Home Observation Measurement for the Environment
HR	Hazard Ratios
ICD	International Code of Diseases
IEUBK	Integrated Exposure Uptake Biokinetic Model for lead
ISA	U.S. EPA Integrated Science Assessment for Lead
LCL	Lower Confidence Limit
LRRP	U.S. EPA Lead-based paint Renovation, Repair, and Painting Rule for residences
NHANES	National Health and Nutrition Examination Survey
NTP	National Toxicology Program
ORs	Odds Ratios
P&CBs	public and commercial buildings
PbB	blood lead
RECS	Residential Energy Consumption Survey
SAB	Science Advisory Board
TSCA	Toxic Substances Control Act
UCL	Upper Confidence Limit
XRF	X-Ray Fluorescence

1. Executive Summary

The U.S. Environmental Protection Agency (EPA) is currently in the process of determining whether lead-based paint hazards are created by renovation, repair, and painting activities in public and commercial buildings (P&CBs), as required under section 402(c)(3) of the Toxic Substances Control Act (TSCA). If the EPA determines that any renovation activities in P&CBs create lead-based paint hazards, TSCA directs EPA to address those hazards through regulation.

EPA recently released a document for public comment, “Framework for Identifying and Evaluating Lead-Based Paint Hazards from Renovation, Repair, and Painting Activities in Public and Commercial Buildings” (79 FR 31072; FRL9910-44). This Framework document described, in general terms, how EPA could identify and evaluate hazards in P&CBs.

The current document, “The Approach for Estimating Exposures and Incremental Health Effects due to Lead During Renovation, Repair and Painting Activities in Public and Commercial Buildings” (referred to hereafter as the “Approach”) describes in detail the methods and Approach EPA is considering to estimate potential environmental concentrations, lead body burdens, and incremental health effects related to exposure to lead from renovations in P&CBs.

The Approach describes how EPA is modeling the potential overall magnitude and distribution of estimated renovation-related health effects due to lead exposure from a P&CB renovation, taking into account background lead levels and health effects when no such renovation exposure occurs. Based on information developed through the Approach, renovation-related health effects will be estimated as the difference between total health effects (background plus renovation-related) and background. Exposures from renovation activities that disturb lead-based paint are connected to subsequent health effects in children and adults through modeling. Separate Monte Carlo-based models were constructed for the analysis of exterior and interior renovations of P&CBs.

In constructing the Monte Carlo-based modeling Approach, a key distinction is made between three kinds of input variables: scenario, sampled, and fixed variables. Scenario variables were treated discretely, and when they are combined determine the overall number of exposure scenarios. Sampled variables were varied within the Monte Carlo iterations to capture population-wide variations. EPA did not have enough information to create a distribution for fixed variables, and they were set to central tendency values. The interior analysis modeled approximately 300,000 scenarios using 3,000 Monte Carlo iterations, and the exterior analysis modeled approximately 30,000 scenarios, using 10,000 Monte Carlo iterations. This resulted in approximately 1.2 billion total modeling iterations, which are believed to adequately describe the range and variability of scenarios considered in this analysis.

The exterior renovation of a P&CB can generate aerosolized lead dust, which is transported through the air, and particulate debris, which is not transported through the air. The ambient air concentrations and lead deposition rates were estimated using the AERMOD dispersion model. Penetration of airborne aerosolized lead dust through the outer shells of buildings is a greater source of exposure than deposition and track-in of lead dust from exterior soils and hard surfaces. The exception to this occurs when high-emitting exterior activities result in elevated soil concentrations at close receptor buildings where many people are expected to enter each day.

The interior renovation of a P&CB can generate aerosolized lead dust and particulate debris within the vicinity of the disturbed lead-based paint. Dust loadings are estimated within the work area, the work room, and adjacent rooms. Dust loadings were estimated through close review and refinement of variables from the Dust Study and were found to increase with the intensity of the job and with smaller room sizes. All variables that impact loadings were grouped and a representative range of loadings for all combinations of possible renovation activities was derived. The range of loadings can be updated with additional information related to renovation activities (frequency, duration, intensity), should such information later become available. For the Approach, EPA used a Geographic Information Systems-based methodology to estimate the number of different types of P&CBs and the distances between different categories of receptor buildings and renovated P&CBs.

An important component of the Approach is how blood and bone lead were modeled. The renovation scenarios modeled for the Approach result in short-term exposures, which are best reflected in blood lead levels. The renovation causes a short-term spike in blood lead. Over a relatively short period of time, blood lead concentrations return to background levels. In contrast, bone is a long-term storage site for lead in the body. Both blood and bone lead were modeled using the Leggett model, which EPA updated in coordination with one of the original model developers. Key model parameters were scaled for children, bone transfer rates were evaluated and updated, and the model results were calibrated against measured data sources for both children and adults. The updated Leggett model performed well when evaluated using the National Health and Nutrition Examination Survey (NHANES) data for children and occupational lead smelter data for adults, indicating good agreement with both these measured data sources and IEUBK model estimates.

The Approach estimated blood lead in two ways. A lifetime average blood lead value was estimated for children and adults by allowing the lifetime variable to vary with the exposure scenario, as defined by the age of an exposed individual at the start of the renovation activity and the time for the individual's blood lead to return to the background level. Concurrent blood lead levels were also saved from the Leggett model at nine different post-renovation time points (1 month, 5 months, 10 months, 15 months, 20 months, 25 months, 30 months, 40 months, and 50 months).

Concentration-response (C-R) functions based on studies reported in the lead health effects literature were applied to blood lead estimates assuming no renovation ("background"), and from corresponding scenarios including a renovation, to estimate the incremental renovation-related health effects. There is model parameter uncertainty in the estimated health effects that occur at any given blood lead value, as indicated by the lower and upper confidence intervals reported for the function, and the Approach incorporated this model parameter uncertainty in the estimation of the effects.

Overall trends across different scenarios matched the direction of trends in the related input variables, with conditions describing higher exposures resulting in higher incremental health effects. For the common metric of blood lead, children elicit a higher response than adults given the same exposure scenario. Blood lead levels are highest at 1 month post-renovation and lowest at 50 months. This trend reverses for bone-lead. Lifetime blood lead estimates are higher in children than adults, and generally fall between 1-month and 50-month estimates. In the Monte Carlo model, some effect estimates fall below levels that can be quantified with accuracy.

The results presented in the Approach encompass all combinations of scenarios that were modeled. The overall magnitude and distribution of results for lead dust loadings, blood lead, and renovation-related health effect changes are presented to help provide context for the Approach. Further discussion of what the Approach currently presents and how information from the Approach could be used in future EPA activities is provided in Section 2.1

2. Scope of Analysis and Overview of the Approach

2.1. Scope

The results described in the Approach will be used for EPA's assessment of the potential range of health effects that could result from P&CB renovations. The results presented here are not intended to, and do not, represent a distribution of exposure or health impacts that mimics exposure across the U.S. population, but instead, represents hypothetical individuals experiencing hypothetical exposure scenarios. EPA is using this initial analysis to understand what types of renovation scenarios should be considered as EPA works to determine whether P&CB renovations create lead-based paint hazards.

The Approach presents a broad range of possible exposure scenarios, including those which may be very high and unlikely and others that might be very low. It is important to note is that each scenario predicts health impacts to a hypothetical individual under a specific set of conditions that define an exposure scenario. While one iteration within an exposure scenario predicts health impacts for a hypothetical individual, the thousands of iterations within an exposure scenario represent a range of exposures to thousands of hypothetical individuals that are possible within that scenario. Any single scenario distribution incorporates the variability across the sampled variables included in the Approach.

The results presented in the Approach, in combination with other additional information, will be evaluated in a subsequent step to inform EPA in determining whether or not hazards are created from the renovation of P&CBs. EPA plans to consider other additional information including but not limited to: the likelihood that a hypothetical scenario occurs, the baseline cleaning and work practices used in the P&CB renovation industry, the frequency of different kinds of renovation activities occurring within P&CBs in the United States, the number, types, and locations of individuals that may be exposed in a given scenario, and the magnitude of health effects that EPA considers to be adverse (and therefore a hazard). Given the additional work necessary, the summary of hypothetical results presented in the

Approach should not be interpreted as an assessment of whether or not hazards are created from the renovation of P&CBs.

Once the frequency of occurrence of each scenario has been determined, EPA can apply a weighted average of the individual scenario results in order to create an estimated population-level distribution of blood lead changes and resulting estimated health effects for the U.S. population. However, in this Approach document, a broad range of results for hypothetical scenarios are shown. It is therefore critical to understand that the percentage of scenarios that share a specific outcome is not equivalent to the percentage of the U.S. population expected to experience this specific characteristic.

2.2. Conceptual Models

As a first step in developing the Approach for estimating exposure to lead from renovation of P&CBs, a conceptual model was designed. Conceptual models are diagrams that show the steps needed to connect sources of exposure, fate and transport, uptake, and ultimately health effects.

Figures 2-1 and 2-2 display the conceptual models for both the interior and exterior renovation analyses and an overview of the types of input variables that were used in the Approach. The modeling Approach connects the emitted lead dust from the renovation to the subsequent health effects in children and adults. This linkage is accomplished by estimating the renovation-related air, soil, and dust concentration time series, lead intake from both renovation and background sources, blood lead levels from both the renovation and background sources (estimated at specific post-renovation times and as a lifetime average), adjusted blood lead levels based on biokinetic differences across the population, and the incremental health effect changes due to renovation activities.

In general, the conceptual model uses building parameters and renovation parameters to estimate the air, soil, and dust concentrations associated with the renovation. The Approach modeled different types of P&CBs to capture a range of building occupancy patterns, uses, sizes, room configurations, air exchange rates, and cleaning methods for buildings found in the United States.

For the Approach, activity patterns were incorporated to determine how much of the time the hypothetical children and adults are in contact with the renovation-derived lead as opposed to background levels in other locations. A blood lead model was used to estimate the blood and bone lead values associated with the exposure concentrations. Concentration-response functions linked the blood lead estimates with estimates of the associated health effects in children and adults. Modeled bone lead values were saved for potential future use if concentration-response functions for health effects based on bone lead concentrations are developed.

EPA estimated renovation-related dust loadings, soil concentrations, air concentrations, blood lead, bone lead, and incremental health effect changes for both interior and exterior modeling. Here, “renovation-related” refers to the total post-renovation blood lead and health effect minus any blood lead or health effect that would have occurred at background lead exposure levels. Renovation-related metrics can be applied to media concentrations, blood lead, or health effects. The renovation-related values were estimated by finding the total post-renovation blood lead and subtracting the background blood lead the person would have had in the absence of a renovation. Another metric considered is the time for environmental media and blood lead to return to background (or pre-renovation) levels.

The conceptual models in Figures 2-1 and 2-2 also provide an overview of the types of input variables that are needed for the Approach.

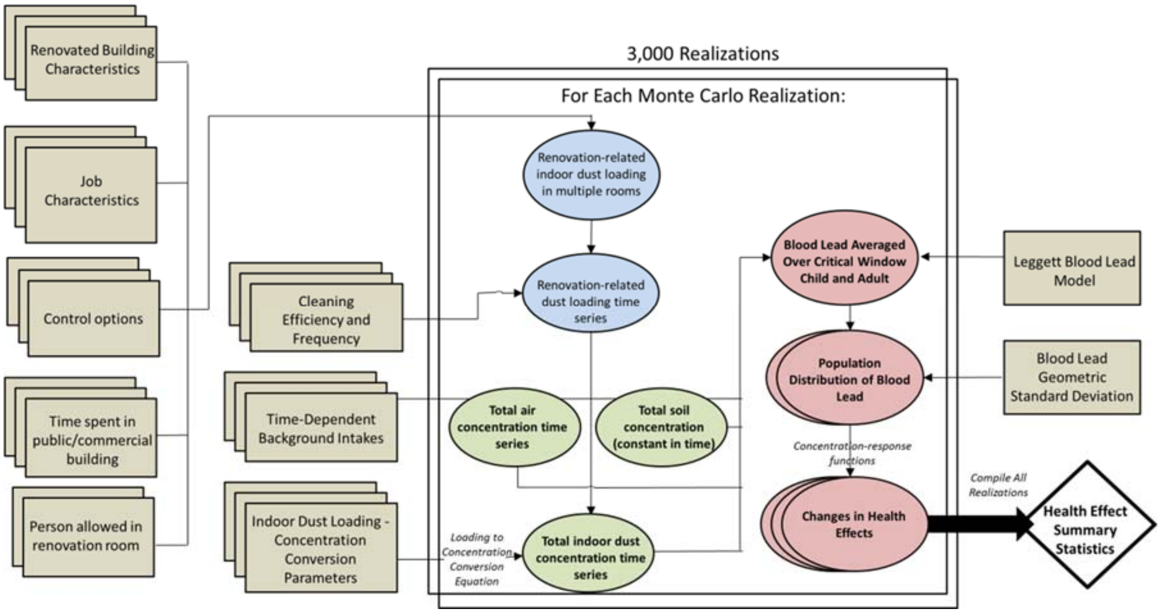


Figure 2-1. Conceptual Model for the Interior Analysis

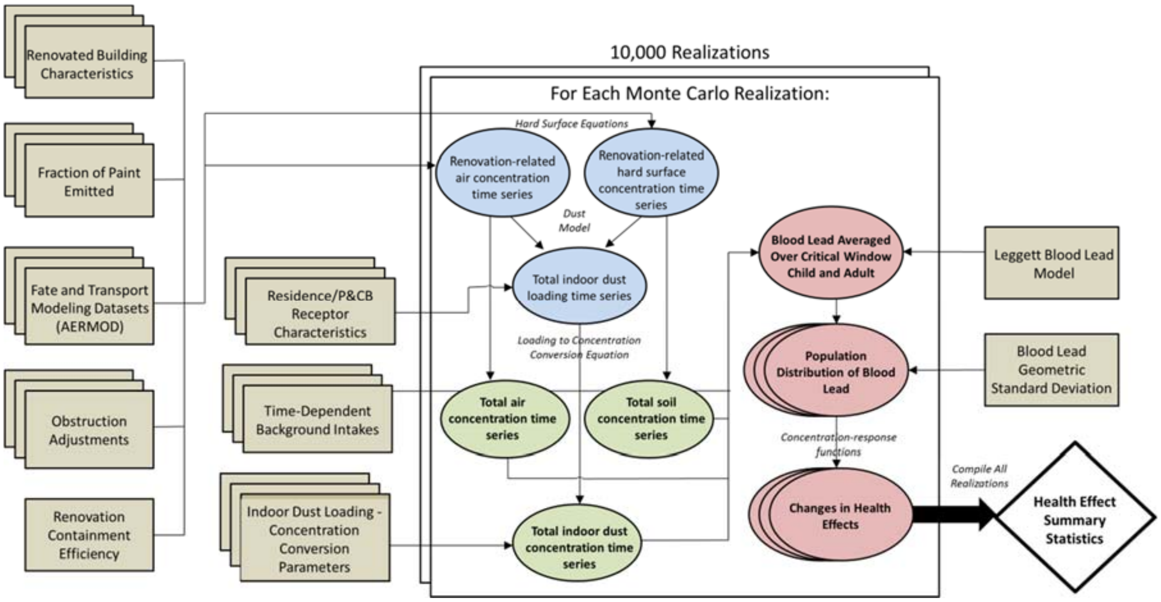


Figure 2-2. Conceptual Model for the Exterior Analysis

2.3. Models Chosen

The models for estimating the media concentrations and blood lead levels were chosen with three specific goals:

1. To use peer-reviewed models wherever possible,
2. To avoid models that require more inputs than can be determined realistically using existing data, and
3. To remain consistent, when possible, with the 2008 lead-based paint renovation, repair, and painting (LRRP) analysis for residences (US EPA 2008), while updating any models that have been improved since then.

For the exterior analysis, EPA used AERMOD (US EPA 2009a) to model the dispersion of lead-containing dust downwind of the renovated building. AERMOD is a Gaussian dispersion model that incorporates meteorological and land-use characteristics. The Approach incorporated adjustments for obstructions to the transport using the AERMOD Plume Rise Model Enhancements (PRIME) model. This model is described in Appendix G.

To estimate the indoor dust loadings resulting from the airborne renovation-derived lead at nearby receptor buildings, a mass-balance indoor dust model was used. The model incorporated air exchange between the indoor and outdoor environments, indoor deposition, indoor resuspension, cleaning frequency and efficiency, and track-in of dust from outdoor soil and hard surfaces. This model is described in Appendix J.

A Monte Carlo model was constructed for the Approach separately for exteriors and interiors using the Python programming language (Python 2012). The model consisted of several modules that perform variable sampling and calculations based on input files specifying the distributions of parameter values, such as the AERMOD air concentration files, indoor dust and outdoor soil concentration files, and the Leggett model uptake tables. Each lookup and calculation step was designed as a separate function in the code. These modules provided the overall model with data about how environmental concentrations vary over time, and how hypothetical individuals of different ages come into contact with these environmental concentrations based on age-driven activity patterns and exposure factors. After verifying the calculations being performed, test cases were run in the model and trends across model scenarios were examined for the purposes of quality assurance.

EPA used a recently updated version of the 1993 Leggett biokinetic blood lead model (Leggett 1993) for estimating both childhood and adult changes in blood lead. The Leggett model enables incorporation of short-term (less than 1 month) changes in exposure levels and modeling of both children and adult blood lead levels. The tissue volumes and key age-dependent pharmacokinetic parameters used in the model were recently updated to better calibrate the model for the age groups that were modeled. This model is described in Section 5 and Appendix M.

2.4. Variables and Renovation Activities Covered

Scenario variables in the Approach were variables that had a predetermined set of possible values. A complete list of the scenario variables (Table 2-1) and the renovation activities (Table 2-2) incorporated into the Approach are provided below. The selection of renovation activities was driven by the needs of the economic analysis and the available data sources, and they cover both paint removal and other renovation activities.

Table 2-1. Scenario Variables in the Approach

Variable	Scenario Variables	
	Exterior	Interior
Renovation activities	✓	✓
Control options	✓	✓
Renovated building use type	✓	✓
Vintage of renovated building	✓	✓
Size of renovated building	✓	(Use Configuration)
Configuration of renovated building	(Use Size)	✓
Size of renovated and adjacent rooms	N/A	✓
Size of job area in the room	N/A	✓
Location of person within building (in workspace or adjacent) or distance of person from the renovated building (receptor distance)	✓	✓
Whether receptor building is carpeted	Not Scenario (Sampled)	✓
Age range (children, young adults, older adults)	✓	✓
Health effects	✓	✓

Each renovation activity was modeled at various intensities. The intensity of an activity varied based on the job size and number of paint layers removed. Job size was related to the type of building where the renovation occurred.

Renovation activities can occur individually or in various combinations. Large renovation jobs consist of several combined renovation activities. EPA assumed that combined renovation activities were performed concurrently rather than sequentially and chose to model a person's most recent exposure (either individual or combined renovation activities). This was done due to lack of available information on frequency and sequence of multiple renovation activities and to avoid additional complexity introduced if these assumptions were not made, in terms of the number of modeling runs required.

Table 2-2. Renovation activities considered in the Approach.

Activity type	Exterior	Interior
Paint Removal Activities		
Power Sanding (with and without HEPA)	✓	✓
Torching	✓	
Heat Gun	✓	✓
Needle Gun (with and without HEPA)	✓	
Dry Scrape	✓	✓
Other Activities		
Cabinet Removal		✓
Cutouts		✓
Remove Window, No Saw		✓
Remove Window, Saw		✓
Exterior Trim Replacement	✓	
Exterior Door Replacement	✓	
Demolition	✓	✓

2.5. Time Series of Exposures and Population Activity Patterns

Renovation activities generally occur over a short-term period and vary depending on the type of renovation activity (individual or combined) and the size of the job. The dust-generating phase is quicker than the rest of renovation phase, which is quicker than the routine cleaning phase. See Figure 2-3 for a visual depiction of these phases.

Interior renovations (dust-generating and rest-of-renovation phases together), on average, were estimated to last approximately 8 weeks. Estimates ranged from less than a day to 7 months (Mossman et al., 2009). This phase varied depending on the type of activity following the lead-based paint renovation activity. For example, if four windows were removed from a room during the dust-generating phase, the length of the rest of renovation phase would equal the amount of time required to install four new windows.

The dust-generating portions of exterior renovations, on average, were estimated to last approximately 1 week. Estimates ranged from 1 day to 4 weeks (Capouch 2011; Mossman et al., 2009). The rest of the renovation phase was not explicitly modeled because this phase was not expected to affect exposure levels at the receptor building where people are exposed. See appendix D for a further discussion of renovation duration.

The time for media concentrations to return to background levels varied across the interior and exterior analysis. The average and 95th percentile values for time to background in the exteriors analysis across all scenarios were 88 and 464 days, respectively. The average and 95th percentile values for time to background in the interiors analysis across all scenarios were 503 and 1,505 days, respectively. This value was largely determined by the cleaning frequency and efficiency in the receptor building (which in turn varied by floor and building type).

Figure 2-3 illustrates this generic time series, using exposure to indoor dust as the primary exposure pathway. Exposure to ambient air resulted in a similar peak during the dust-generating phase of the renovation activity but quickly returned to background after the renovation activity stopped. Exposure to soil results in a similar peak during the dust-generating phase, but the soil lead concentration remained elevated over time due to lead's persistence in the soil. Exposure to particles on hard surfaces outdoors resulted in a similar peak during the dust-generating phase but returned to the background level more quickly than soil due to removal from rain events.

Within this time series, activity patterns were varied by age group and building type based on the Consolidated Human Activity Database (CHAD) database (US EPA 2014a). Exposure to adults and children depended on how and when they interacted with these concentrations. The age of the person and the amount of time they spend in the building affects their resulting blood lead levels. People typically spend less time in P&CBs than they do in residences.

Occupants in the receptor building spent varying amounts of time in the building, referred to in this document as "time spent." The time-spent distributions were age and building-type dependent, and the person was exposed to renovation-related lead concentrations only when they were in the affected building. When they were away from the building (and prior to the renovation), they were assumed to have age-specific background lead exposure estimated from the NHANES survey (CDC 2012).

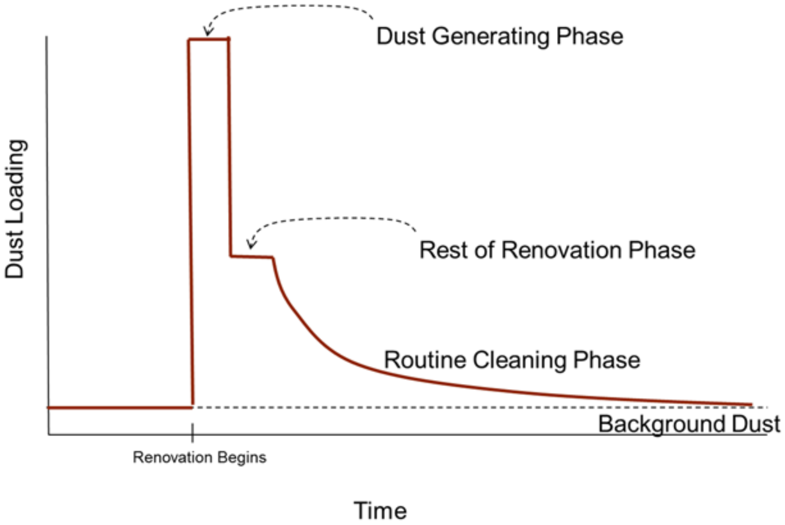


Figure 2-3. Illustration of Renovation and Post-Renovation Exposure Phases

2.6. Exposure Metrics Selected for the Analysis

After individuals in receptor buildings are exposed to renovation-related lead, an increase in overall body burden of lead is likely. The key metrics examined in the Approach are blood lead and bone lead. The half-life of lead in blood is relatively short (approximately 30 days) while the half-life of lead in bone, depending on which bones are considered, is years to decades (US EPA 2013). The renovation introduced a spike in blood lead, and then the blood lead concentrations returned to background levels, as shown in Figure 2-4. In contrast, bone represents a long-term storage site for lead in the body. Thus, bone lead can be interpreted as a record of past history of lead exposure. The renovation caused an increase in bone lead that might stay with the individuals through the remainder of their lives, also shown in Figure 2-4. Figure 2-4 is adapted from Figure 1 of Hu et al. (1998).

Over a person’s lifetime, that person might be exposed to multiple renovation activities that would follow the generic time series described above and shown in Figure 2-3. Modeling exposures to multiple renovations in multiple types of buildings over a person’s lifetime would introduce significant uncertainty into model estimates. Instead, the Approach estimated incremental health effects from a person’s most recent exposure to a renovation activity.

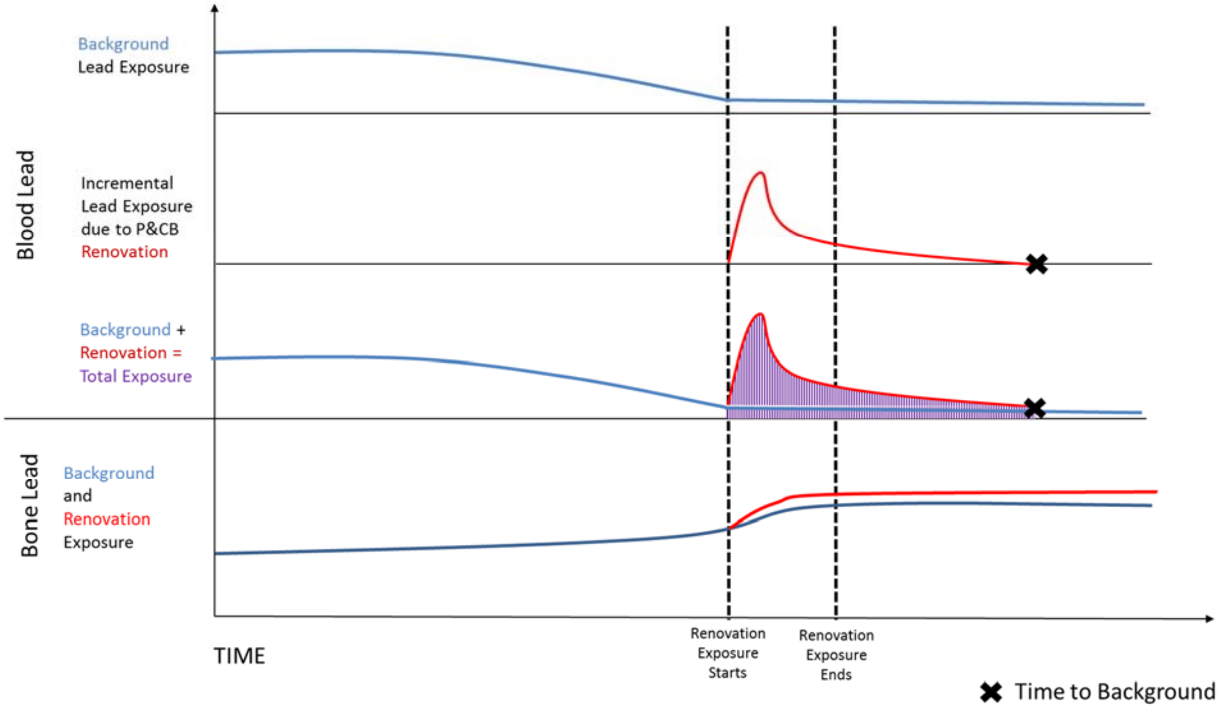


Figure 2-4. Schematic of Renovation Effects on Blood and Bone Lead (adapted from Hu et al., 1998)

2.7. Health Effects and Age Groups Covered in the Analysis

Based on a review of existing child and adult epidemiology studies, described in Section 6.1, the health effects in Table 2-3 were selected for inclusion in the analysis. Where appropriate, due to apparent differences in the magnitude of an effect, or due to limitations in the applicability of a concentration-response function as taken from the literature, the selected health effects were modeled only for the age ranges specified in Table 2-3 (which is described further in Section 6.1).

Table 2-3. Health Effects Included in the Approach

Health Effect	Age Ranges		
	Children 0–10	Adults 18–49	Adults >50
IQ Changes	✓		
Low Birth Weight[a]		✓	
Kidney Effects		✓	✓
Cardiovascular Disease Mortality (CVDM)		✓	✓

[a] Blood lead levels in women aged 18–49 were used to estimate the reduction in birth weight of their infants.

The Approach modeled building occupants in three age ranges: 0–10, 18–49, and 50–80 years. The age groups were defined based on the approximate range of ages in the health effect studies (0–10 for IQ decrements, 18–49 for women with low birth weight infants, and 18–80 for cardiovascular disease mortality and kidney effects). Children aged 11–17 will also be exposed to renovations that could result in health effects. They were not modeled as part of the Approach. As described in Section 6, health effect studies with strong concentration-response relationships for this age-group were not identified. EPA might, however, explore the feasibility of estimating lead body burden and health endpoints (e.g., low-birth-weight infants for women aged 15–17) for this age group later.

In the 0- to 10-year age group, children will have diverse activity patterns, including varying amounts of time spent in different buildings. EPA notes that buildings defined as child occupied facilities were not assessed in this Approach. EPA bound the modeling parameter of time spent for young children, and will continue to evaluate this over time to ensure that child occupied facilities are not modeled or assessed as P&CBs.

2.8. Incorporating Variability

Numerous factors influence the exposure from interior and exterior renovations. They include the number of layers of paint and the lead content of the paint on the renovated building, type of renovation activity performed, particle sizes released during the renovation activity, age of the exposed individual at the time of the renovation, biokinetic characteristics of the individual, and building characteristics affecting indoor lead dust levels such as cleaning frequency, cleaning efficiency, flooring type, air exchange rate, building size, and room size. Factors that further affect the exposure from exterior renovations include the prevailing meteorology, distance from the renovated building, and presence of obstructions between the exposed individual's location and the renovated building.

These factors are expected to vary widely across building types and renovation events. For this reason, probabilistic modeling techniques (specifically, Monte Carlo analysis techniques) were used to estimate distributions of health effect changes using distributions of key input variables. Where possible, the overall modeling Approach built on and refined the analysis EPA performed for the 2008 residential LRRP rule (US EPA 2008).

2.9. Monte Carlo Methods

In constructing the Monte Carlo-based modeling Approach, a key distinction was made between different sets of input variables. **Scenario variables** are variables that were treated discretely. Each scenario variable had a predetermined set of possible values. Changes in health effect statistics were independently estimated for all combinations of the scenario variable values. Each unique combination of scenario variables is referred to as a **scenario**. Scenario variables are listed in Table 2-1, and more detail is provided in Appendices A (exteriors) and B (interiors).

For each scenario, several other variables were allowed to vary to capture differences across the population. Each variable has a specified range of values and associated probabilities that these values occur. Monte Carlo modeling was performed by calculating health effect changes using various combinations of input variable values. Each independent calculation of an estimated blood lead value and corresponding health effect change for a set of input values is known as a Monte Carlo **iteration** and represents one hypothetical individual. During an iteration, a value was chosen (randomly sampled) for each input variable, and the associated blood lead value and corresponding health effects were calculated. This was done for both background exposure (without renovation) and renovation-related exposure (varied by scenario). One iteration resulted in a blood lead estimate and corresponding health effect estimates for this hypothetical individual's background exposure (without renovation), renovation-related exposure, and total exposure (background plus renovation-related exposures). Therefore, the renovation-related effects are the difference between total and background values. This procedure was then repeated thousands of times for each exposure scenario.

To distinguish the variables that were allowed to vary across iterations from the variables that define a scenario, the former variables are referred to as **sampled variables**. As opposed to scenario variables, results from sampled variables were not aggregated in the analysis; instead, their variations were used to take into account population-level variability in the renovation-related health effects. All sampled variables are listed in Appendices A and B.

A third set of variables was not varied; instead, these variables were set to their central tendency values for all scenarios and iterations. These variables, referred to as **fixed variables**, are listed in the tables in

Appendices A and B. These variables are not expected to substantially affect the estimates and generally have limited data available.

To perform the Monte Carlo analysis, each scenario was run thousands of times (where each run is referred to as an "iteration"). Testing indicated that 10,000 iterations for exteriors and 3,000 iterations for interiors were appropriate to optimize the combination of accuracy and run-time efficiency. For each iteration within each scenario, a value was selected randomly for every sampled variable from its associated distribution.

Each model iteration represents one hypothetical individual's exposure within that scenario and resulting blood lead and health effects. The distribution of characteristics provides an estimate for thousands of hypothetical individuals per scenario.

3. Estimating the Renovation-Related Media Concentrations during Exterior Renovations

When paint removal or another dust-generating activity is performed on the exterior of a P&CB, exposure can occur from several exposure pathways, as listed below and illustrated in Figure 3-1:

Inside the Renovated Public and Commercial Building:

1. Airborne lead-dust penetrates the building shell.
2. Lead-dust near the perimeter is tracked into the building.

Inside Nearby Residences and Public and Commercial Buildings:

3. Airborne lead-dust travels downwind and penetrates other building shells.
4. Airborne lead-dust near the building travels downwind, deposits on the hard surface/soil, and is tracked into the downwind buildings.

Near the Renovated Public and Commercial Building:

5. Airborne lead-dust and deposited lead on hard surface/soil near the renovated building results in exposure to building occupants when they are outside the renovated building.
6. Airborne lead-dust and deposited lead on hard surface/soil near the downwind building results in exposure to building occupants outside the downwind building.

Each exposure pathway results in elevated environmental concentrations, resulting in possible exposures for individuals who spend time in these microenvironments.

To capture exposure pathways in Cases 3, 4, and 6, a series of empirical data and peer-reviewed models was used to estimate the different media concentrations shown in red and italics for the downwind building in Figure 3-1: airborne lead dust, dust lead, and hard surface/soil lead. This section describes the overall methodology used to estimate the lead emission rates related to the renovation activity, wind transport and deposition (fate and transport modeling), air and hard surface/soil concentrations, and indoor lead dust levels in the downwind building. The exposure pathways to occupants inside and directly outside the renovated building (Cases 1, 2, and 5) are covered via incorporation into the interior modeling Approach (Section 4).

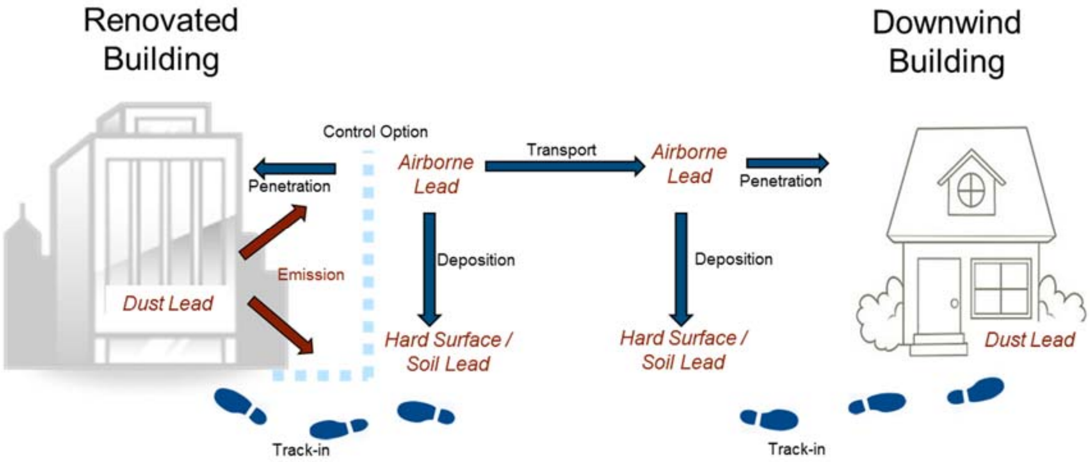


Figure 3-1. Illustration of Exposure Mechanisms for Exterior Renovations

3.1. Renovation Characteristics

To characterize the lead emitted during a renovation event, the renovated building and the renovation job were defined for each exposure scenario. The renovated building and renovation activities were characterized using the list of the variables described below. A discussion of how the values were determined for this analysis is provided in Appendix A.

3.1.1. Characterizing the Renovated Building

To characterize the renovated building for a given exposure scenario, the key variables included:

- area of the building footprint,
- number of stories in the building,
- building vintage,
- square footage of building components (painted wall, trim, windows/doors),
- average percentage of lead in the paint, and
- average number of layers of paint.

The number of layers of paint and percentage of lead in the paint, in general, were correlated with the building vintage. Based on available data, the Approach estimates that older buildings had more layers of paint, which had higher lead content (US EPA, 1998a, EPA 2007a). Thus, building vintage was incorporated into the estimates for each of these variables.

This list does not include building use type. For the exterior analysis, EPA assumed that the overall function of the building will not affect the emission of lead during renovation activities. The only exception is agricultural buildings; these buildings are typically in rural rather than urban areas, so the fate and transport modeling accounted for this difference, as discussed in Section 3.4.

3.1.2. Characterizing the Renovation Jobs

To characterize the renovation job for a given exposure scenario, the key variables included:

- renovation activity,
- fraction of paint removed,
- rate of renovation, and
- job duration.

Job duration depends on the size of the building and the rate of renovation. In general, EPA assumed that a renovation job is performed on the entire painted surface area of a building for a given component. For example, if the job is a paint removal activity, EPA assumed that the estimated layers of paint were removed from the wall surface area of the entire building. The exception is demolition; in this case, the jobs were characterized as involving only one wall.

3.2. Lead Emission Rates during the Renovation Job

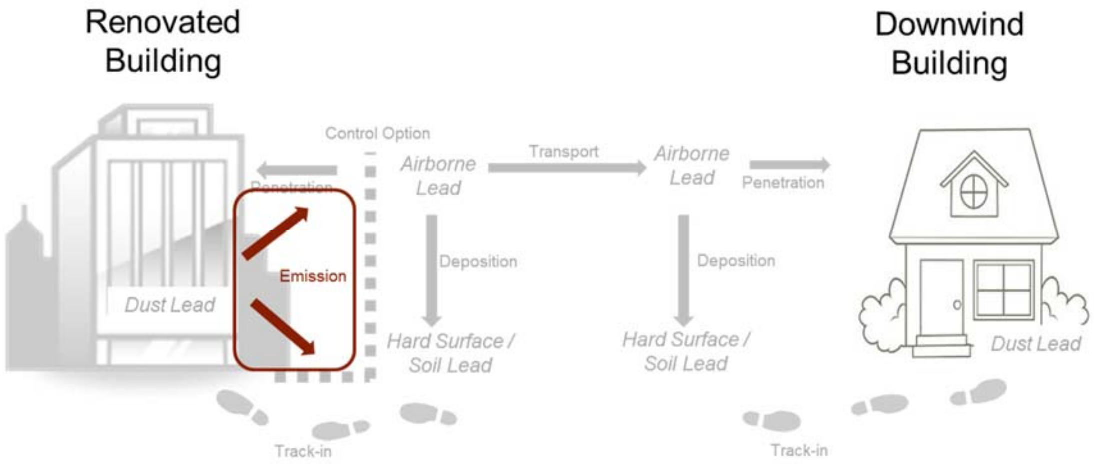


Figure 3-2. Illustration of Emission from Renovation Activity

The lead removed from the building exterior consists of a spectrum of particle sizes. For the purpose of this assessment, three particle classes were defined and later grouped into two categories:

Category 1: Particulate Debris

1. **Bulk debris**: large particles that are readily seen and easily cleaned after the job, and
2. **Particulate debris**: intermediate particles that do not travel downwind but are more difficult to see and clean after the renovation.

Category 2: Aerosolized Particles

3. **Aerosolized particles**: smaller particles of a size and density that enable them to aerosolize and travel downwind. These particles can be deposited farther from the renovated building vicinity.

Thus, lead persists post-renovation in two particulate classes (Figure 3-2): aerosolized particles (upward arrow) and particulate debris (downward arrow). This section describes how emissions were characterized for both types of particles.

3.2.2. Aerosolized Particles

The emission rates for aerosolized particles were estimated based on the total amount of lead removed during the job, the estimated fraction of the removed lead that becomes aerosolized, and the duration of the job:

$$AerEmissRate = \frac{LeadRemoved \times AerFrac \times UnitConv}{JobDuration}$$

Where:

AerEmissRate = the mass of lead emitted per hour (μg/h)

LeadRemoved = the total amount of lead in the paint that is removed (μg)

AerFrac = the fraction of the total amount of removed lead that becomes aerosolized

JobDuration = the total duration of the job (h)

UnitConv = a conversion factor to convert from hours to seconds and mg/cm^2 to g/ft^2.

AerFrac was estimated using information contained in the Draft Final Report on *Characterization of Dust Lead Levels After Renovation, Repair, Painting Activities* (US EPA, 2007a), hereafter referred to as the Dust Study. The Dust Study contains a series of experiments depicting renovation activities in homes and schools with lead based paint and then sampling the resulting lead loadings. The *AerFrac* variable is independent of the lead content in the paint and the size of the job; instead, it characterizes the amount of removed paint that becomes aerosolized. By characterizing emissions using this fraction, the Dust Study experiments were normalized to account for differences in lead content in the paint, differences in job size, and differences in job configuration to yield estimates of the aerosolized fraction for each experiment. The estimation of this variable is documented in Appendix H.

The variable *LeadRemoved* was estimated using the amount of lead on the wall at the start of the job per unit area, the fraction of paint removed during the job, and the total job surface area:

$$LeadRemoved = XRF \times FractionRemoved \times JobArea \times UnitConv$$

Where:

LeadRemoved = the total amount of paint lead that is removed (μg)

XRF = the x-ray fluorescence (XRF) measurement of lead in the paint per square cm of wall (mg/cm^2 wall)

FractionRemoved = the fraction of the total layers of paint that are removed during the job

JobArea = the area of the building that was disturbed during the renovation (ft^2)

UnitConv = a conversion term to convert from mg to μg and cm^2 to ft^2.

The amount of lead on the wall, also referred to as wall loading, at the start of the job (*XRF*) was captured by XRF measurements, and a nationally representative data source (the National Survey of Lead and Allergens in Housing, HUD 2002) was used to estimate the XRF distribution for the various building vintages. This variable is described in Appendix C.1.7.

The fraction removed (*FractionRemoved*) is intended to reflect that not all layers of paint are removed during a repainting job. When a wall surface is repainted, it is usually first prepared by removing a fraction of the existing paint rather than all the paint on the wall. This fraction can vary by the substrate type (wood, metal, and stucco result in different surface preparation methods), the method used to remove the paint (mechanized or heating techniques enable faster removal of more layers than scraping methods), and the condition of the existing paint (more paint is likely to be removed if the paint is highly degraded). A representative value of 15 percent was selected for the amount removed during surface preparation, as described in Appendix H. For the other types of activities (e.g., trim removal, door removal, demolition), the fraction was assumed to match the fractions estimated to have been removed in these jobs in the Dust Study (US EPA 2007a).

Both the *JobArea* and the *JobDuration* variables depend on assumptions about the size of the building. These variables are discussed in Appendix D.

The final emission rate equation, after substituting in the *LeadRemoved* equation, is;

$$AerEmissRate = \frac{XRF \times FractionRemoved \times JobArea \times AerFrac \times UnitConv}{JobDuration}$$

Where:

AerEmissRate = the mass of aerosolized lead emitted per hour (μg/h)

XRF = the XRF measurement of lead in the paint per square cm of wall (mg/cm^2 wall)

FractionRemoved = the fraction of total layers of paint removed during the job

JobArea = the area of the building disturbed during the renovation (ft^2)

AerFrac = the fraction of the total mass of paint removed that becomes aerosolized

UnitConv = a conversion factor to convert from hours to seconds and mg/cm^2 to g/ft^2

JobDuration = the total duration of the job in hours (h).

3.2.3. Particulate Debris

The mass emitted as particulate debris was estimated in a way similar to how aerosolized particulate was estimated. Rather than an emission rate, however, the particulate debris calculation directly estimates the amount of lead per square foot of ground after the renovation (the lead loading). No fate and transport modeling is required for this particle class, so the loading can be directly estimated.

$$ExtPartDebMassEmit = XRF \times JobArea \times PartDebFrac \times UnitConv$$

Where:

ExtPartDebMassEmit = lead mass emitted to the hard surface from particulate debris (μg)

XRF = the XRF measurement of lead in the paint per square cm of wall (mg/cm^2 wall)

JobArea = the area of the building disturbed during the renovation (ft^2)

PartDebFrac = the fraction of paint on the wall emitted as particulate debris

UnitConv = a factor to convert from g to μg and cm^2 to ft^2

The fraction of the paint emitted as particulate debris was estimated from a study on removal of lead paint from bridges (Lee and Domanski 1999). The study evaluated the removal due to sandblasting and the subsequent release of particles. The study estimated that, of the bulk material generated (bulk debris and particulate debris, or the total particulate after subtracting the portion aerosolized), an additional 6 percent would have an aerodynamic diameter less than 50 μm. This estimate was judged to be an appropriate definition for the particulate debris fraction in the absence of other data. Thus, the *PartDebFrac* variable was estimated as:

$$PartDebFrac = (1 - AerosolFrac) \times 0.06$$

Where:

$PartDebFrac$ = fraction of paint on the wall emitted as particulate debris

$AerosolFrac$ = fraction of paint on the wall emitted as aerosol.

3.3. Control Options

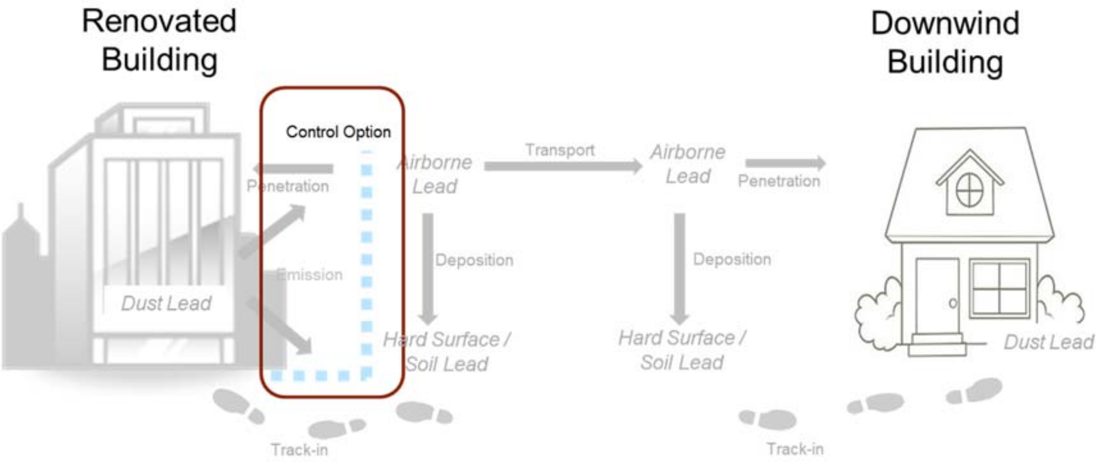


Figure 3-3. Illustration of Control Options for Renovation Activity

Four options for controlling lead dust generated by exterior renovations of P&CBs were considered (Figure 3-3): (1) the use of horizontal containment around the renovation, (2) the use of vertical containment, (3) the combined use of horizontal and vertical containment, and (4) the replacement of high-dust-generating activities with low-dust-generating activities. Modeling was also done with none of these control options in place.

As discussed in Section 3.1, lead is emitted and persists post-renovation in two different particulate size categories: aerosolized particles and particulate debris. As a mitigating factor, the use of horizontal containment further eliminates a large portion of the particulate debris from the renovation site. Using a vertical containment, a significant fraction of aerosolized lead is captured and deposits in the immediate vicinity of the renovated building.

Containment options were incorporated into the model via containment efficiencies applied to the lead emission rates. Horizontal plastic was assumed to be placed around the perimeter of the renovated building to a distance of 10 ft from the building edge along each wall. The dust that fell onto the horizontal plastic was assumed to be evenly distributed on the plastic by the end of the renovation, when the plastic and dust that remained on top were assumed to be removed. Not all deposited lead mass will be captured by the horizontal plastic; the percentage of the dust depositing on the ground that is captured by the horizontal plastic is referred to as the containment efficiency. This value was estimated using dust loadings measured above (i.e., captured by plastic) and below (i.e., not captured by the plastic) the horizontal plastic in the Dust Study. The overall average for all activities, 95 percent, was used as the horizontal containment efficiency.

Vertical containment also was modeled as constructed around the perimeter of the building 10 ft from the building edge, resulting in the same building-specific area of containment. Fewer data were available to calculate the efficiency of dust capture by vertical containment. Iyiegbuniwe et al. (2006) presented data for the efficiency of containments used during bridge de-leading by abrasive blasting and found an efficiency of 91 percent for lead particles. In the absense of additional data, this value was used for the vertical containment efficiency for all renovation activities.

When vertical containment was used alone, the captured dust was assumed to be evenly dispersed on the ground within the area of containment at the end of the renovation. When vertical plastic was used in conjunction with horizontal plastic, the captured dust was modeled as falling onto the horizontal plastic and subsequently being removed with the plastic at the end of the renovation.

The effect of replacing higher dust-generating activities with lower dust-generating activities was estimated by taking the difference of separate model runs for both the original and replacement activities and determining the net reduction effect. In this Approach, the following differences were estimated: needle gun without HEPA vs. needle gun with HEPA and power sanding without HEPA vs. power sanding with HEPA. The with-HEPA activities were assumed to have a 90 percent efficiency when compared to their no-HEPA activity counterparts. This is further described in Appendix D.

3.4. Fate and Transport Modeling

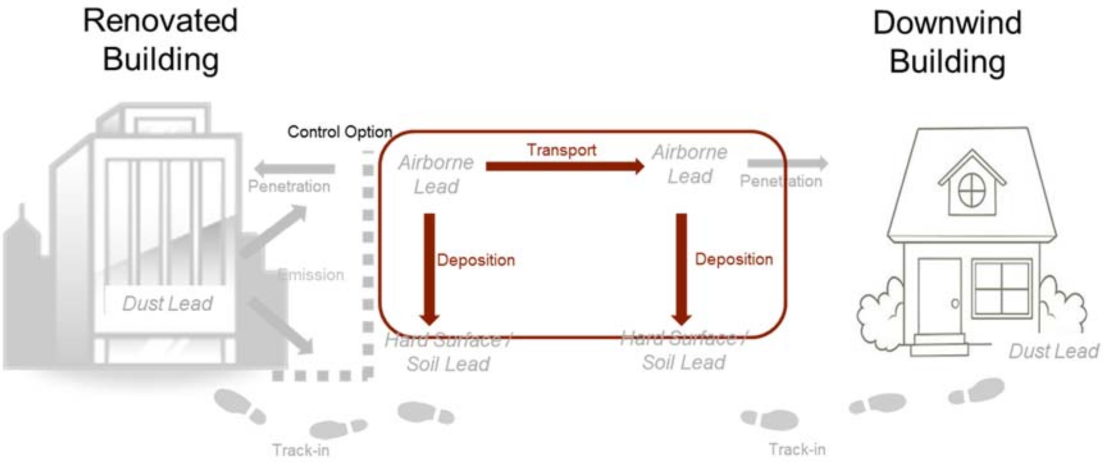


Figure 3-4. Illustration of Transport and Deposition

The renovation-related air lead concentrations and lead deposition rates (Figure 3-4) were estimated using the AERMOD dispersion model (version 13350; 12/16/2013) (US EPA 2009a). According to the *Revision to the Guideline on Air Quality Models* (US EPA 2005), AERMOD represents the most robust air quality model for source-specific modeling when evaluated against monitoring data. To prepare the meteorological data, both AERSURFACE (first version; 01/2008) and AERMET (version 13350; 12/16/2013) were used to preprocess the data (US EPA 2009b).

AERMOD is a Gaussian air dispersion model. It is not a mass-conserving fluid dynamics model nor does it simulate feedback mechanisms, such as resuspension of deposited lead from soil. Theoretically, a computational fluid dynamics (CFD) model could be a more appropriate selection for this application, but no CFD model is readily available that can support this type of generalized assessment designed to represent the range of conditions in the United States. Early scoping runs showed that resuspension does not significantly influence the air concentrations and subsequent indoor dust loadings. Therefore, air concentrations were estimated using the AERMOD values during the renovation and were set to zero following the renovation.

AERMOD requires inputs that characterize the meteorological conditions; location, strength, and duration of the emissions; particle size distribution (for estimating the deposition rate); and receptor distance from the source, orientation, and height. To capture the natural variability in these input parameters, the Approach was designed to allow these parameters to vary by scenario or probabilistically or both. A set of AERMOD runs was performed to generate the necessary outputs for all permutations of these inputs.

Assumptions were made for each set of inputs to focus the analysis on a feasible number of AERMOD runs while ensuring the model predictions were generalizable enough to capture the range of possible air concentrations of aerosolized lead-dust experienced by the hypothetical individuals around the renovated buildings. By varying all of the above parameters, more than 5,000 AERMOD simulations were performed. Each simulation assumed a unit emission rate of 1 gram/second, and the complete set of average air concentrations was compiled into a database used as inputs to the Monte Carlo model. The unit emission rate was used so that the runs could be easily scaled later by multiplying by the actual renovation-specific emission rate. During each Monte Carlo iteration, probabilistic sampling was used to select an AERMOD simulation to use for a given iteration.

For the Approach, agricultural buildings were modeled with AERMOD's rural option; all other receptor building types were modeled with AERMOD's urban option. AERMOD's urban modeling option parameterizes one of the effects of the urban heat island—the decreased nighttime cooling that creates a "convective-like" nighttime boundary layer with enhanced heating and turbulence compared to an adjacent, nonurban area. Because the renovations occur only during the day and the urban effect occurs primarily at night, the difference between simulated air concentrations using the urban versus rural model setting is expected to be minimal. Early test runs indicated that differences in modeled air concentrations were less than 1 percent in approximately 90 percent of the simulated scenario-days. For the small percentage of scenarios where this distinction does make a difference, EPA could consider additional data sources that describe how often different building types occur in urban or rural locations by adding this as a sampled variable.

3.4.1. Receptor Buildings

Receptor buildings were assumed to be one of five unique types of buildings:

1. Residences
2. P&CB – Commercial Buildings
3. P&CB – Schools and Child Occupied Facilities
4. P&CB – Industrial Buildings
5. P&CB – Agricultural Buildings

Each different receptor building type was characterized with appropriate dimensions, air exchange, and track-in rates, as discussed in Appendix E.

The locations were placed along 16 evenly spaced radials emanating from the center of the renovated building. Receptor building locations upwind in a given hour of the renovation have no renovation-derived concentration of aerosolized lead-dust for that hour, while receptor building locations downwind of the renovation have the maximum concentrations. The assumption was that a receptor building would be equally likely to be located along any of these radials, so the probability of each occurring was 1/16 (or 0.0625) in the Monte Carlo model.

Receptor building locations were placed so that the average distance from the nearest wall of the renovated building equaled each of 6 target distances along each radial: 5 ft, 50 ft, 150 ft, 300 ft, 650 ft, and 800 ft. A schematic of the receptor building locations in relation to the renovated building is presented in Figure 3-5. These distances were selected to provide higher resolution close to the renovation and to extend far enough to capture all locations where the change in dust loadings, blood lead concentrations, and health effects due to renovation were at or approaching background levels. The closest receptor distance at 5 ft is meant to capture the air concentrations and depositions for the renovated building itself, and the results from these runs were incorporated into the interior modeling.

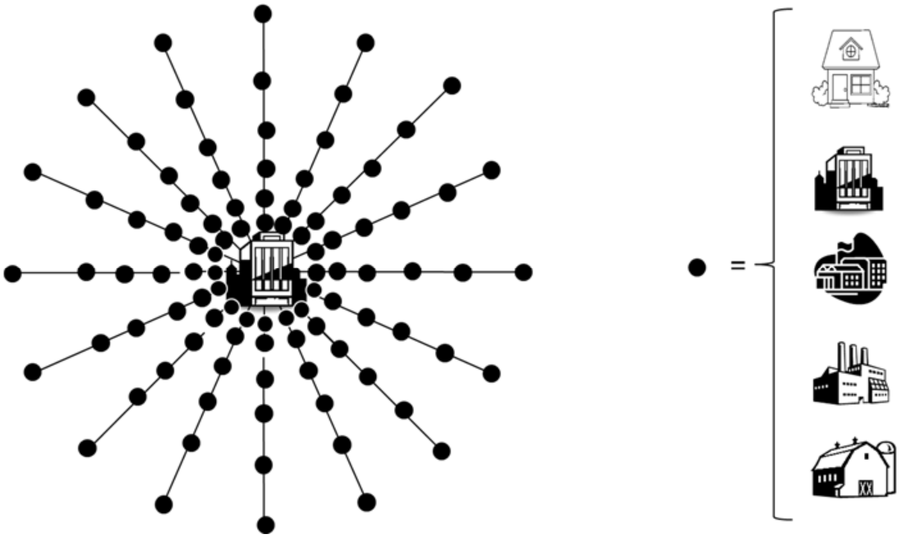


Figure 3-5. Summary schematic of example renovated building and locations of receptor buildings.

Early scoping results showed that track-in of lead that is deposited on exterior surfaces around the receptor building location contributes much less to combined exposures than atmospheric transport of lead dust directly into the receptor location. In the case of receptor buildings that are very near to the renovation building, however, track-in can affect indoor loadings, particularly when considering debris generated from the renovation that is too large to be atmospherically transported. As such, track-in of the bulk dust particulate debris and the dust that is captured within the containment area is considered at the 5 ft receptor location.

The receptor building heights were simulated as 1, 2, or 3 or more stories. The DOE 2005 Residential Energy Consumption Survey (RECS) (US EIA 2005) reports the frequency of different numbers of stories in the U.S. housing stock. The Commercial Building Energy Consumption Survey (CBECS) reports the frequency of different numbers of stories in commercial buildings (US EIA 2003). The height of each story varied by building type and was derived from Department of Energy (DOE) reference buildings

(Deru et al., 2011). Residences were assumed to have 8-foot ceilings, commercial buildings were assumed to have 9-foot ceilings, schools were assumed to have 11-foot ceilings, and agricultural and industrial buildings were assumed to have 28-foot ceilings (Deru et al., 2011). The heights in AERMOD of individuals exposed within receptor buildings were set to correspond to the height of an individual (1.8 meters or 5.9 feet) above the height for each building story. For example, in one-story buildings, the breathing height for an individual in the building is 5.9 feet. For buildings greater than one story, the individual's breathing height is the sum of the individual's height and the ceiling height of building, which varies by building type.

3.4.2. Meteorological Conditions

Meteorological conditions, most notably wind direction, wind speed, and turbulence, are key factors in characterizing the transport of lead emissions across relatively small distances. Capturing all the potential meteorological conditions near a renovated public/commercial building is not possible. The meteorological conditions captured in this Approach, however, were designed to be generalizable to renovations occurring during any season and in any part of the country.

An analysis was performed to determine sets of meteorological conditions that together would be representative of the United States. Similar methodology has been used previously for other EPA assessments, including modeling near roadway pollutants for the Office of Transportation and Air Quality (US EPA 2011).

Nine climate regions within the United States, as defined by the National Oceanographic and Atmospheric Administration (NOAA), were selected (NCDC 2011). These regions are reproduced in Figure 3-6. The percentage of the U.S. population represented by each climate region is presented in Table 3-1. These percentages were used to construct the cumulative probability of selecting a given climate region in the Monte Carlo model.

Some of these climate regions contain coastal areas and others do not. For climate regions where the selected representative station was coastal, available meteorological stations within the region were analyzed to determine an additional inland representative. If a region was represented by two stations (one coastal and one inland), each was given equal probability of occurrence in the Monte Carlo model. These 14 stations were then processed using AERMET for use in the AERMOD air dispersion and deposition model. The modeling for the current analysis used high-frequency wind data and AERMINUTE to reduce calm or missing wind values in the hourly wind data, and it also used other substitution methods for missing values of important meteorological variables. The full data processing, analysis, and preparation methods are further described in Appendix G.

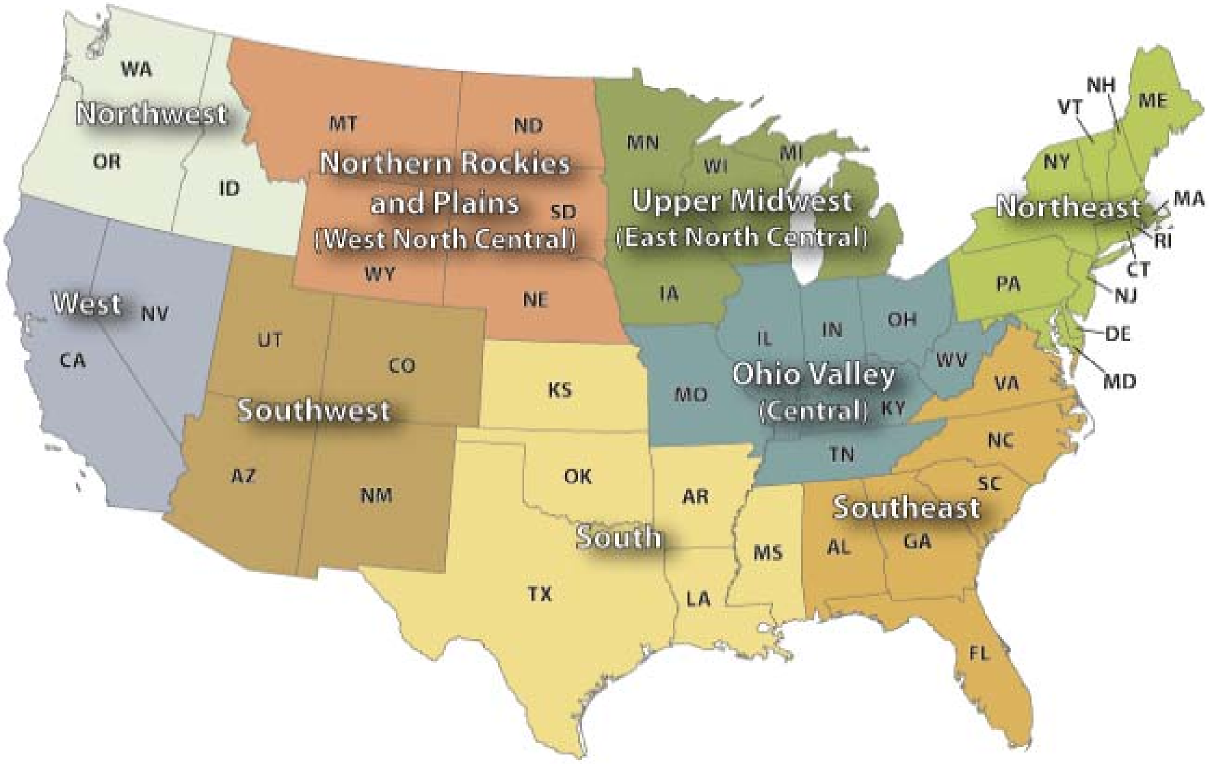


Figure 3-6. NOAA Climate Regions

Table 3-1. Population distribution by climate region.

Climate Region	Percentage of Population in Region	Cumulative Probability Used in Monte Carlo Model
Upper Midwest	7.82%	0.0782
Northeast	20.25%	0.2807
Northwest	3.96%	0.3203
South	13.78%	0.4581
Southeast	18.11%	0.6392
Southwest	5.31%	0.6923
West	13.05%	0.8228
Northern Rockies and Plains	1.59%	0.8387
Ohio Valley	16.13%	1.0000

3.4.3. Obstruction Adjustment

The presence of obstructions between the source building and the receptor building can either increase or decrease the amount of renovation-derived lead-containing dust to which individuals are exposed. The windfield is influenced by the buildings such that emitted dust can be channeled around and over the obstruction building and concentrated in a mixing “rotor” zone on the leeward side of the building.

Thus, individuals located near the obstruction might be exposed to either a larger concentration (in the rotor zone) or smaller concentration (outside the rotor zone).

The Approach accounts for this potential obstruction effect by including an obstruction adjustment factor. The distribution was determined from a set of test runs with different renovation-building obstruction-building combinations with respect to distance and orientation. The distribution fit to the test cases is:

For the 1st to 32nd percentiles: $ObsAdj = 0.15 \times \ln(\mathrm{perc})+1.15$

For the 33rd to 87th percentiles: $ObsAdj = 1$

For the 88th to 100th percentile: $ObsAdj = \exp(\mathrm{perc}^{25})$

Where:

$ObsAdj$ = obstruction adjustment

$Perc$ = percentile of distribution

The obstruction adjustment was also bound by the overall minimum and maximum found experimentally, 0.1 and 5.3, respectively. More information about the derivation of this distribution is available in Appendix G.

3.5. Air Concentrations

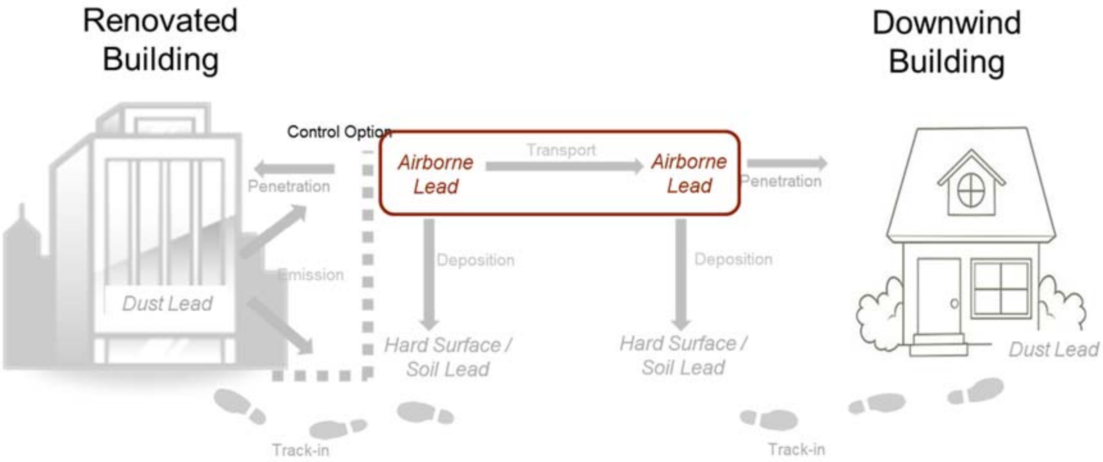


Figure 3-7. Illustration of Air Concentration

The air concentration time series at each receptor building during the renovation (Figure 3-7) is estimated as:

$$RecptAirConc = AERMODair \times EmissRate \times ObstructAdj \times (1 - VertPlasticEff)$$

Where:

ReceptAirConc = the air lead concentration time series at the receptor ($\mu g/m^3$)

AERMODair = the modeled air concentration assuming unit emissions (1 g/s) in AERMOD for the particular scenario and iteration ($\mu g/m^3$)

EmissRate = the lead aerosol emission rate as in Section 3.2 (g/s)

ObstructAdj = the obstruction adjustment, as discussed in Section 3.4.3

VertPlasticEff = the containment efficiency of the vertical plastic, set to zero if there is no containment or set to the renovation activity-specific value if containment is present.

The lists of all the AERMOD variable values for the particular scenario and for the particular Monte Carlo iteration were used to select the correct AERMOD model output file. If the total job was assumed to be performed on only a portion of the building (such as one wall), only a fraction of the AERMOD air concentrations was used (i.e., ¼ of the full run if only one wall was disturbed). The renovation duration is also corrected by multiplying by the same fraction when estimating the emission rates.

3.6. Outdoor Hard Surface and Soil Concentrations

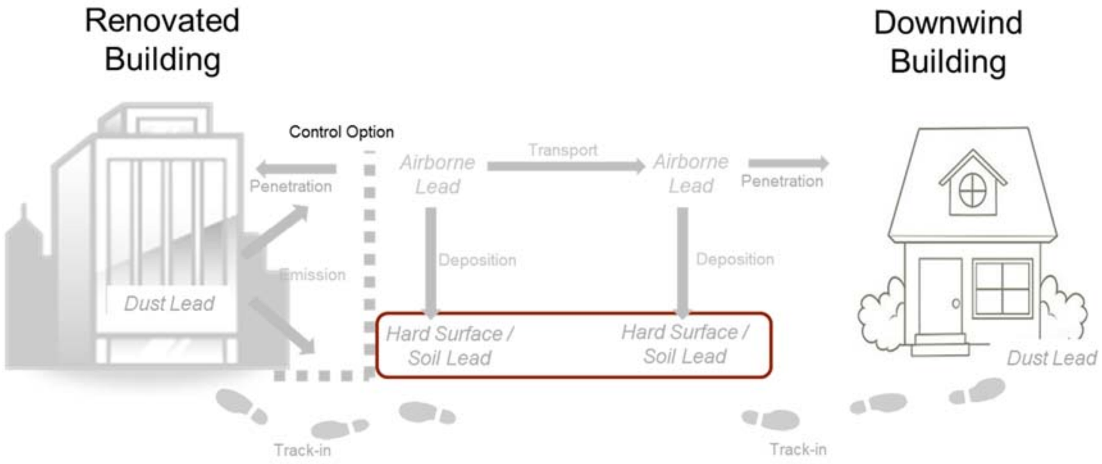


Figure 3-8. Illustration of Soil Lead Estimation

The primary source of exposure to renovation-derived lead for occupants of buildings near the renovation site is expected to be aerosolized particulates emitted during the renovation and later incorporated into indoor dust. For children and adults living adjacent to the renovated building, however, significant exposure might occur due to track-in, depending on the type of containment used during the renovation. To capture this potential exposure, the lead concentrations on hard surfaces (such as sidewalks or entryways) and in soil around the renovated building are estimated (Figure 3-8). Track-in was assumed to occur from walking on the ground and carrying the associated lead into an adjacent receptor-building location. This section discusses the equations used to construct the track-in lead concentration time series. Appendix E provides a discussion of how each input parameter value was estimated.

To capture these processes, first the lead dust loadings on the hard surface from both aerosolized and bulk particulate were calculated, taking into account the containment being used. No pedestrian foot traffic was assumed to occur in the job site during the renovation. Thus, the available loading from track-in during the renovation was set to zero. The renovation aerosol lead remaining on the ground near the renovated building and available for track-in immediately after the renovation was estimated as:

$$\begin{aligned} &ExteriorAerosolMass \\ &\qquad = AerEmissRate \times RenoDur \times VertPlasticEff \times (1 - HorPlasticEff) \\ &\qquad \times UnitConv \end{aligned}$$

Where:

ExteriorAerosolMass = lead mass on hard surface from aerosolized particulate (μg)

AerEmissRate = the lead aerosol emission rate (g/s)

RenoDur = the total number of hours in the renovation job (determined by the renovation rate/crew size and the number of blocks in the building) (h)

VertPlasticEff = the containment efficiency of the vertical plastic, set to zero if there is no containment or set to the renovation activity-specific value discussed in Section 2.5 if containment is present

HorPlasticEff = the containment efficiency of the horizontal plastic, set to 0 if there is no containment or set to the renovation activity-specific value if containment is present

UnitConv = a factor to convert from h to sec and g to µg.

The renovation particulate debris lead remaining on the ground near the renovated building and available for track-in immediately after the renovation was estimated as:

$$ExtPartDebMass = ExtPartDebMassEmit \times (1 - HorPlasticEff)$$

Where:

ExtPartDebMass = lead mass on hard surface from particulate debris (µg)

ExtPartDebMassEmit = lead mass emitted to the hard surface from particulate debris (µg)

HorPlasticEff = the containment efficiency of the horizontal plastic, set to zero if there is no containment or set to the renovation activity-specific value if containment is present.

This first equation builds on the *AerEmissRate* from Section 3.2.2, and the latter builds on *ExtPartDebMassEmit* in Section 3.2.3.

The lead loading around the renovated building immediately following the renovation was then calculated as:

$$ExteriorLoading = \frac{ExteriorAerosolMass + ExteriorPartDebMass}{ContainmentArea}$$

Where:

ExteriorLoading = lead loading on hard surfaces (µg/ft^2)

ExteriorAerosolMass = lead mass on hard surface from aerosolized particulate (µg)

ExteriorPartDebMass = lead mass on hard surface from particulate debris (µg)

ContainmentArea = area over which renovation debris falls (ft^2).

This lead will settle on both hard surfaces (sidewalks, etc.) and the soil that surrounds the renovated building. On hard surfaces, it will mix with other particles on the surface and slowly be washed away due to runoff and other processes. In soil, it will mix into the upper soil layer and remain in the soil, given the residence time of lead in soil is between 50 and 1000 years (Kaste et al., 2003; Klaminder et al., 2006).

For hard surfaces, the removal was assumed to occur at a specified frequency in discrete events (such as rain events) that remove a specified fraction of lead during each removal event. The removal frequencies and efficiencies are discussed in Appendix F. The hourly time series was constructed by:

- Repeating the loading for each subsequent hour until a removal event is scheduled to occur;
- Multiplying the loading by the removal efficiency (*TrackInRainEff*) for the hour just after the removal event; and
- Repeating Steps (1) and (2) for the duration of the simulation or until the loading reaches a level close to, but nominally above, 0 (selected to be 0.01 µg/ft^2), whichever comes first. Because the hard surface loading is exponentially decaying, it will not reach exactly 0, so a value very close to 0 was selected.

For soil, the removal frequency is set to zero so that the lead is not removed from the upper layer during the course of the simulation.

The dust estimation equations and biokinetic blood lead model both require the track-in levels to be in terms of lead concentration rather than loading. Thus, the loading time series was converted to a lead hard surface concentration time series by assuming a dust density, dust layer depth, and dust layer porosity on the hard surface and soil and adjusting the units:

$$TrackInConcen = \frac{ExteriorLoading}{TrackInDepth \times TrackInDensity \times (1 - TrackInPorosity) \times UnitConv}$$

Where:

TrackInConcen = exterior hard surface or soil lead concentration (µg/g)

ExteriorLoading = lead loading on hard surface or soil (µg/ft^2)

TrackInDepth = depth of particulate layer available for track-in (m)

TrackInDensity = density of particulate layer available for track-in (g/m^3)

TrackInPorosity = porosity of particulate layer available for track-in (unitless)

UnitConv = conversion of ft^2 to m^2 (unitless).

The parameter values for the dust density and dust layer porosity are the same for both hard surfaces and soil. The layer depth (*TrackInDepth*) differs between hard surface and soil, with hard surface set to a nominal value of 1 mm and soil set to 1.5 cm. All three variables are discussed in Appendix F.

3.7. Indoor Dust Concentrations during the Renovation

This section describes how indoor dust loadings and concentrations (Figure 3-9) were estimated after incorporating the contributions from the air concentrations (via penetration), the soil/hard surface concentrations (via track-in), and the effect of routine cleaning.

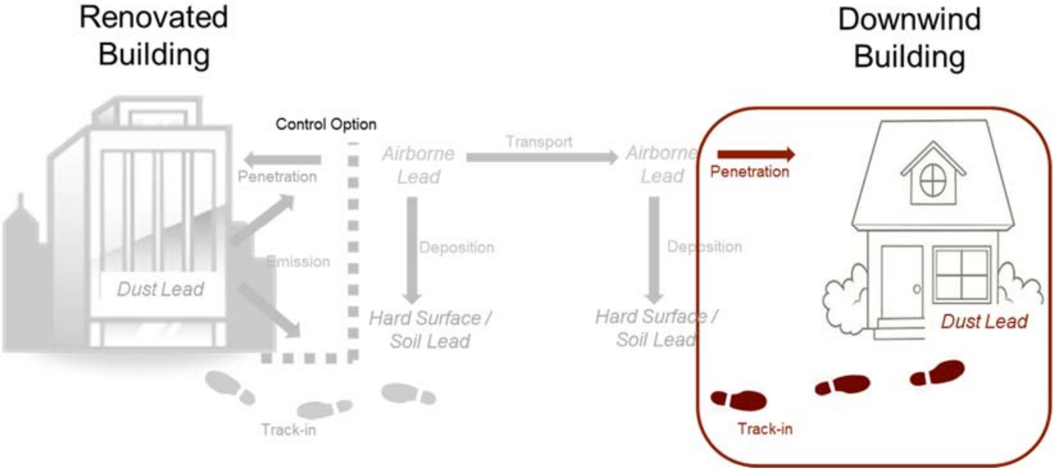


Figure 3-9. Illustration of Dust Loading Estimation

3.7.1. Indoor Dust Loadings

To estimate the indoor floor lead dust loading resulting from exterior renovations transported to nearby buildings, a mechanistic mass-balance model was developed. The model is an extension of the hybrid mechanistic-empirical model used in the lead National Ambient Air Quality Standard exposure and risk assessments (US EPA 2007b). The results of the model have not previously been used in an EPA analysis, although the model received positive reviews from the SAB when presented as part of the review of the proposed approach for revising the lead hazard standard (US EPA 2010). This model accounts for the two dominant sources of lead in indoor dust from exterior renovation activities: penetration of lead-containing ambient air into the indoor environment and tracking of lead from exterior soil or hard surfaces into the home. Removal occurs due to air exchange and routine cleaning. The model preserves the total mass in the system and accounts for the accumulation of lead on the floor and in the indoor air.

The indoor air mass balance equation accounts for penetration into the indoor environment, removal due to air exchange, deposition from the air to the floor, and resuspension from the floor to the air. The equation representing these processes is:

$$\begin{aligned}\frac{dINAIR_{Pb}}{dt} = {} & AirExchangeRate \times DustModelPen \times ReceptAirConcen \times ReceptorVolume \\ & - AirExchangeRate \times INAIR_{Pb} - DustModelDep \times INAIR_{Pb} + DustModelResus \\ & \times FLOOR_{Pb}\end{aligned}$$

Where:

$dINAIR_{Pb}/dt$ = change in time of the indoor air lead mass (µg/h)

AirExchangeRate = air exchange rate (h^{-1})

DustModelPen = penetration efficiency (unitless)

ReceptAirConcen = concentration of lead in ambient air ($\mu g/m^3$)

ReceptorVolume = volume of the receptor location (m^3)

$INAIPR_{Pb}$ = indoor mass of lead in air (µg)

DustModelDep = deposition rate (h^{-1})

DustModelResus = resuspension rate (h^{-1})

$FLOOR_{Pb}$ = mass of lead on the floor (µg).

The floor mass balance equation accounts for deposition of lead from the air onto the floor, resuspension of lead from the floor into the air, tracking of lead from outdoor soil, and removal of lead due to routine cleaning:

$$\begin{aligned}\frac{dFLOOR_{Pb}}{dt} = {} & DustModelDep \times INAIR_{Pb} - DustModelResus \times FLOOR_{Pb} \quad + \ TrackInConcen \\ & \times PartTrackingRate \times (1 - MatFrac) \quad - CleanEff \times CleanFreq \\ & \times FLOOR_{Pb}\end{aligned}$$

Where:

$dFLOOR_{Pb}/dt$ = change in time of the indoor floor lead mass (µg/h)

$INAIPR_{Pb}$ = indoor mass of lead in air (µg)

$FLOOR_{Pb}$ = mass of lead on the floor (µg)

DustModelDep = deposition rate (h^{-1})

DustModelResus = resuspension rate (h^{-1})

TrackInConcen = concentration of lead in the tracked-in particles (µg/g)

PartTrackingRate = rate at which particulate is deposited on front mat (g/h)

MatFrac = fraction of total tracked material that is deposited on the front mat (as opposed to the remainder of the house) (unitless)

CleanEff = cleaning efficiency (unitless)

CleanFreq = cleaning frequency (cleanings/h).

In most cases, the above terms represent first-order transfer rates multiplied by the mass in the donor compartment. For example, for the deposition from the air to the floor, the transfer term is the air mass multiplied by the first-order deposition rate. In some cases, an additional efficiency term is included to indicate that only a certain percentage of the total mass is removed. For example, for the routine cleaning, the mass is multiplied by both the removal rate (cleaning frequency) and the removal efficiency (cleaning efficiency). The track-in is characterized as a soil track-in rate multiplied by the lead soil concentration and an efficiency that represents the amount that remains on a mat rather than being spread through the building.

By converting the above mass-balance differential equations to difference equations, the model can be integrated forward in time to find the mass of lead on the floor and in the air at each time step using the time-varying air concentrations from AERMOD and the time-varying outdoor hard surface or soil concentrations. For the Approach, track-in was assumed to occur from soil 50 percent of the time and from hard surfaces the other 50 percent of the time.

Appendices E and J together describe how the input values and distributions for the model were determined. In each case, the variables were characterized separately for each receptor building type (agricultural, industrial, public/commercial, school, and residence). Early scoping results indicated that air exchange rate, cleaning frequency, track-in rate, and the percentage of the receptor-building that is carpet were sensitive variables. Depending on whether adequate information was available in the literature, sensitive variables were varied using probabilistic distributions, and the remaining values were set to central tendency estimates.

Early scoping results showed that when compared to air penetration, track-in of particles from soil and hard surfaces contributed less to indoor dust loadings. Under circumstances where outdoor soil or hard surface concentrations are elevated and more people continuously walk into a building, however, the effect of track-in will be amplified when compared to buildings where people enter less frequently (Hunt et al., 2006). The approach taken to scale track-in to different types of P&CBs is described in Appendix E.

Some variables, including the cleaning efficiency and the resulting amount of lead removed by cleaning, depend on the *total* amount of lead dust in a building rather than just the renovation-derived portion. For this reason, the background indoor dust loading was used as the initial condition in the model, and after the completion of the renovation the cleaning is performed until the total dust loading is just lower than the background level. This background is then subtracted to obtain the renovation-related portion of the dust loading.

3.7.2. Indoor Dust Concentrations

The indoor dust model used for both the exterior and interior approach, provides an estimate of the lead loading in terms of mass of lead per square foot of floor. Biokinetic blood lead models require lead concentrations, or the amount of lead per mass of particulate.

Three data sets were combined to generate an empirical equation to convert lead dust loadings to lead dust concentration (Adgate et al 1995, HUD 2002, Rasmussen et al 2013). The resulting best-fitting equation had the following form:

$$\ln(Conc) = Intercept + Slope \times (\text{Adj} \ln(Load)) + ErrorVariance$$

Where:

$$Adj\ ln(Load)) \quad = \quad \ln(Load) - \text{Average}\ (\ln(Load)).$$

The average ln(*Load*) is the average of the natural logarithms of the measured loadings. The *ErrorVariance* term was incorporated to allow the concentration estimates to vary in different Monte Carlo iterations given the same lead loading input. This term was added to reflect that the underlying data indicate significant spread related to household-specific parameters such as the cleaning frequency, cleaning efficiency, and contributions from outdoor soil versus indoor air. The data-processing and regression analysis are fully described in Appendix K.

4. Estimating the Renovation-Related Media Concentrations during Interior Renovations

When a dust-generating activity is performed on the interior of a P&CB, exposure can occur under several different settings, as listed below and illustrated in Figure 4-1:

1. Exposure to people who are in renovated rooms and inside the work area,
2. Exposure to people who are in renovated rooms and outside the work area,
3. Exposure to people who are in rooms adjacent to renovated rooms, and
4. Exposure to people who are in other parts of the building.

In the diagram, the shaded areas indicate rooms that are being renovated, while the crosshatching indicates where only part of a room is being renovated. For these interior renovations, we considered three phases:

1. The **dust-generating phase**, when the portion of the renovation job expected to generate lead-containing dust is performed. Any cleaning by the contractor occurs after the dust-generating phase.
2. The **rest-of-renovation phase**, when the remainder of the renovation takes place.
3. The **routine-cleaning phase**, when the renovation is complete and the dust levels are slowly returning to background levels due to routine cleaning in the building.

So, lead dust levels could be elevated during all three phases until the lead loading returns to background levels. This section details how the lead dust loading was calculated for different renovation scenarios.

4.1. Renovation Characteristics

To characterize the lead emitted during a renovation event, the renovated building and the renovation job were defined for each exposure scenario, just as in the exterior analysis. This section discusses the characterization of the renovated building and the renovation job, with a complete discussion of the derivation of each variable in Appendices B, C, and D.

4.1.1. Characterizing the Renovated Building

For the interior analysis, the renovated areas within P&CBs were characterized so that the variability within the U.S. building stock was captured. In this analysis, the three variables used to capture the building-specific differences were:

- Building use type,
- Layout of the building, and
- Room sizes and room characteristics in the building.

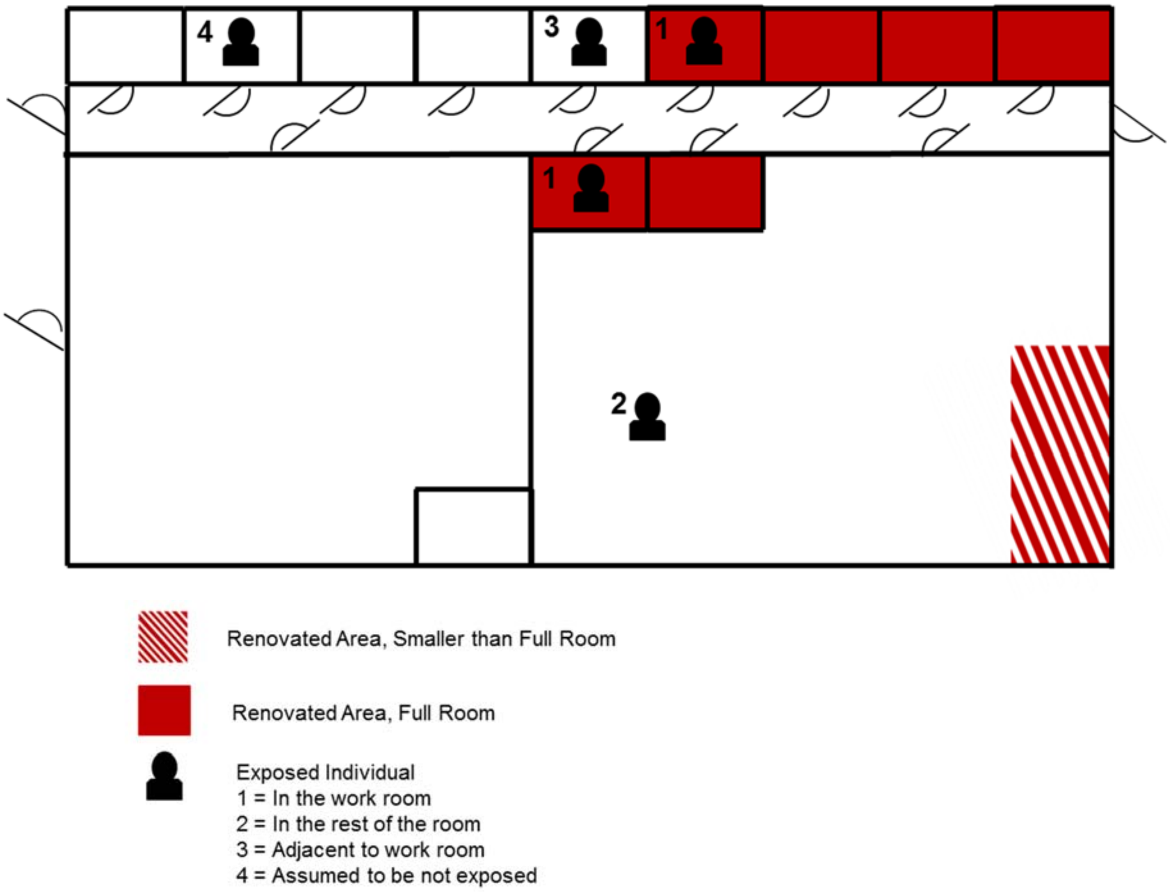


Figure 4-1. Example Building Layout with Different Renovation and Occupant Locations

This section describes how these variable values were assigned for this Approach.

Use Types

Unlike the exterior analysis, where only the exterior attributes of the building will strongly influence exposure, the use type of an interior building will affect key attributes of both the building itself and the amount of time per day people spend in the building. For example, a large supermarket will have one or two large spaces with multiple smaller rooms, and patrons will visit the building only once or twice a week. In contrast, hotels have numerous small rooms, and patrons might stay for days or months at a time.

The CBECS survey provides information about the number of buildings in the United States in different use categories, as shown in Table 4-1 (US EIA 2003). These CBECS categories were mapped to five assessment categories for this Approach, where CBECS categories were grouped according to layouts, room sizes, and expected time spent patterns. Five assessment categories were chosen to ensure adequate coverage of the various building types and also to balance the resource constraints of the Monte Carlo analysis.

Table 4-1. CBECS Buildings and Mapped Assessment Categories

CBECS Category	DOE Categories	Assessment Categories
Office	Small Office Medium Office Large Office	1. Office, outpatient healthcare, and public order/safety
Outpatient health care	Outpatient Healthcare	
Public order and safety		
Non-refrigerated warehouse	Warehouse	2. Warehouse, food sales, religious worship, and public assembly
Refrigerated warehouse		
Food sales	Supermarket	
Religious worship	None	
Public assembly	None	
Food service	Quick Service Restaurant Full Service Restaurant	3. Food service, service, strip shopping mall, enclosed mall, and retail other than mall
Service	None	
Strip shopping mall	Strip Mall	
Enclosed mall	None	
Retail other than mall	Stand-alone Retail	
Education	School	4. Education
Lodging	Small Hotel Large Hotel	5. Lodging, Nursing, inpatient health care, and laboratory
Nursing	None	
Inpatient health care	Hospital	
Laboratory	None	
Other	None	None
Vacant	None	

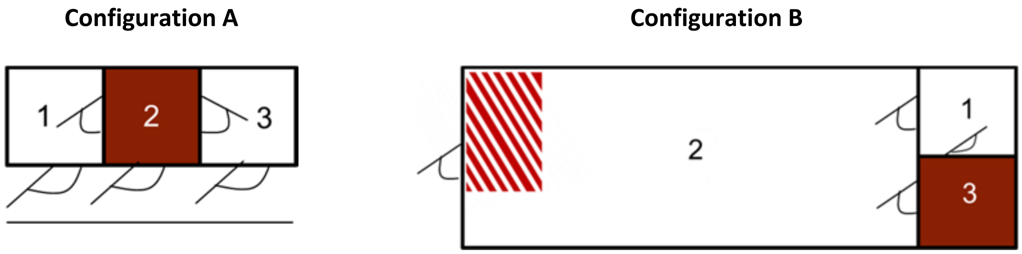
Building Layouts

Buildings in the United States can have numerous layouts, and the precise layout will influence how many people are in proximity to a given renovation job. For this assessment, resource limitations dictated that only a few representative layouts could be captured. As a starting point, the DOE reference buildings (Deru et al., 2011) were used. These reference buildings provide layouts for 14 building types, and each layout comprises a series of zones that correspond to a part of a room, a room, or a group of rooms.

In general, the layouts displayed a few characteristics:

- Some had a single large room with multiple smaller rooms (e.g., food sales, warehouse, stand-alone retail, offices with open floor plans and cubicles), and
- Others had repeating units connected by a hallway or walkway (e.g., schools, hospitals, hotels, strip malls).

Thus, two different layouts were selected for the analysis, as shown in Figure 4-2. The room sizes in the layouts were varied to capture representative buildings in each use type. Each building layout has three rooms. In addition, repeating units of each layout can occur in the same building.


Configuration A

Configuration B

Figure 4-2. Representative Building Layouts Used in the Approach

Based on Dust Study renovation experiment data (see Appendix I), dust levels in rooms adjacent to renovated rooms tend to be one or two orders of magnitude lower than the loadings in the renovated room during the renovation. For this reason, and to constrain the analysis to a reasonable number of scenarios, the following assumptions were made:

- Lead dust is unlikely to travel large distances in the HVAC system (turning off HVAC system and/or covering air intakes during dust-generating activities further prevents the spread of dust through the HVAC system),
- Lead dust loadings decrease exponentially with distance from the renovation activity, and
- The renovation affects only those rooms directly adjacent to a renovated room and the renovated room itself. All other rooms experience no increase in lead loading.

Based on these assumptions, only three rooms were used to estimate the exposure possibilities for a person in the renovated building. If multiple rooms were renovated during a single job, and the total exposure was estimated for a given person situated in one room. As in Figure 4-1, the red hatched area represents a renovated area smaller than a full room and the red solid area represents a fully renovated room.

Room Sizes and Characteristics

Each layout can comprise three rooms of varying sizes, and the DOE reference buildings were used to characterize the set of room sizes for the Approach. The building types in the DOE data were mapped to the assessment building categories, as shown in Table 4-1.

The data provided the size and frequency of each type of zone within the reference buildings. The zones were mapped to rooms based on the expected room layouts in the different building types. Then, two to four room sizes were estimated for each assessment category, as described in Appendix C. Overall, twelve room sizes were selected across the five building categories.

In addition to room size, other characteristics were used to estimate the amount of paint disturbed during a renovation job, including:

- Ceiling height,
- Painted wall area,
- Percent of the room that is glass (window), and
- Fraction of the room covered in shelving attached to walls.

These variables were estimated by assuming that the width-to-length ratio of each room was 2:1 and by using the CBECS and DOE reference building data, as described in Appendix C. The 2:1 ratio is based on the assumption that most rooms are rectangular rather than square. This assumption is consistent with the majority of layouts presented in the DOE reference building data.

4.1.2. Characterizing the Renovation Job

To characterize the renovation job for a given exposure scenario, the key variables include:

- The type of renovation activity or activities,
- Rooms within the configuration that are being renovated,
- Floor area within the job area, and
- Fraction of paint removed.

The activities that comprise the job characterize each renovation. Activities can include a single type of activity or a combination of activities (e.g., a paint removal activity and a window replacement). To characterize the extent of the room that the renovation affects, each renovation job was given an “intensity” in a scenario. This intensity characterizes the fraction of the wall area (paint removal and cutouts) or the fraction of the room components (window replacement and shelving) the job affects.

Including an intensity is particularly important for Configuration B, where one room is very large; in this case, the renovation might affect only a corner, leaving most of the room relatively unaffected. For this reason, a job area is also defined for each job, taking into account the intensity and assuming job areas extend 10 ft out from the wall. This job area was assumed to be relatively isolated from the rest of the room because of the inability of the lead dust to travel the entire extent of the room. The remainder of the room was then treated as if it were an “adjacent” room.

The renovation experiments in the Dust Study indicated that lead dust levels decay exponentially with distance from the disturbed wall, and 10 ft was selected as a job area dimension based on inspection of the shape of the experimental exponential functions across experiments (see Appendices H and I). Any combination of rooms within a building configuration can be renovated, so different scenarios were created to capture different renovation possibilities (US EPA 2007a).

4.2. Lead Released During Renovation

The lead removed from the interior wall and building components consists of a spectrum of particle sizes. As with the exterior analysis, different particle classes were defined:

1. **Bulk and particulate debris**: large particles that are readily seen and easily cleaned after the job, and
2. **Dust debris**: intermediate and small particles that are more difficult to see and clean.

Thus, lead persists post-renovation as dust debris, with the assumption that the renovation crew removes all bulk debris and performs baseline cleaning to remove some of the dust debris before leaving the job site. This section describes how the resulting post-renovation lead loading was characterized for the dust debris particles.

As in the exterior analysis, emissions were characterized using the fraction of wall paint removed that ends up as dust on the floor at the end of the renovation. The equation is:

$$FloorLoad = \frac{LeadRemoved \times DustFrac \times PhaseFactor \times LocFactor}{JobFloorArea}$$

Where:

FloorLoad = the floor lead loading after the renovation (μg/ft^2)

LeadRemoved = the total amount of lead in the paint that is removed (μg)

DustFrac = the fraction of the total amount of removed lead that remains as dust at the end of the renovation

PhaseFactor = a factor that adjusts the post-dust-generating phase room floor loading to the post-cleaning room floor loading, if applicable (see Section 4.2.4) adjacent room floor loading, if necessary

LocFactor = a factor that adjusts the work room floor loading to the adjacent room floor loading, if applicable (see Section 4.2.4)

JobFloorArea = the total job floor area (ft^2).

The variable *LeadRemoved* was estimated using the amount of lead per unit area on the wall at the start of the job, the fraction of that paint that is removed during the job, and the total job surface area:

$$LeadRemoved = XRF \times FractionRemoved \times JobArea \times UnitConv$$

Where:

LeadRemoved = the total amount of lead that is removed (μg)

XRF = the XRF measurement of lead in the paint per square cm of wall (mg/cm^2 wall)

FractionRemoved = the fraction of the total layers of paint that are removed during the job

JobArea = the floor area over which lead dust debris falls (ft^2)

UnitConv = a conversion factor to convert from h to sec and mg/cm^2 to g/ft^2

FractionRemoved is intended to reflect that not all layers of paint will be removed during a typical repainting job. When a wall surface is repainted, it is usually first prepared by removing a fraction of the existing paint rather than all the paint that is on the wall. This fraction can vary by the substrate type (wood, metal, and stucco typically have different surface preparation methods), method used to remove the paint (mechanized or heating techniques enable easier removal of more layers than scraping), and condition of the existing paint (more paint is likely to be removed if the paint is highly degraded). A representative value of 15 percent was selected for the amount removed during surface preparation, as described in Appendix C. For other activities (e.g., trim removal, door removal, demolition), the estimated fractions removed in these jobs were assumed to match those fractions in the Dust Study (US EPA 2007a).

The amount of lead on the wall (XRF, also referred to as wall loading) at the start of the job was captured by XRF measurements. A nationally representative data source (the National Survey of Lead and Allergens in Housing, HUD 2002) was used to estimate the XRF distribution for different building vintages. This variable is described in Appendix C.2.8.

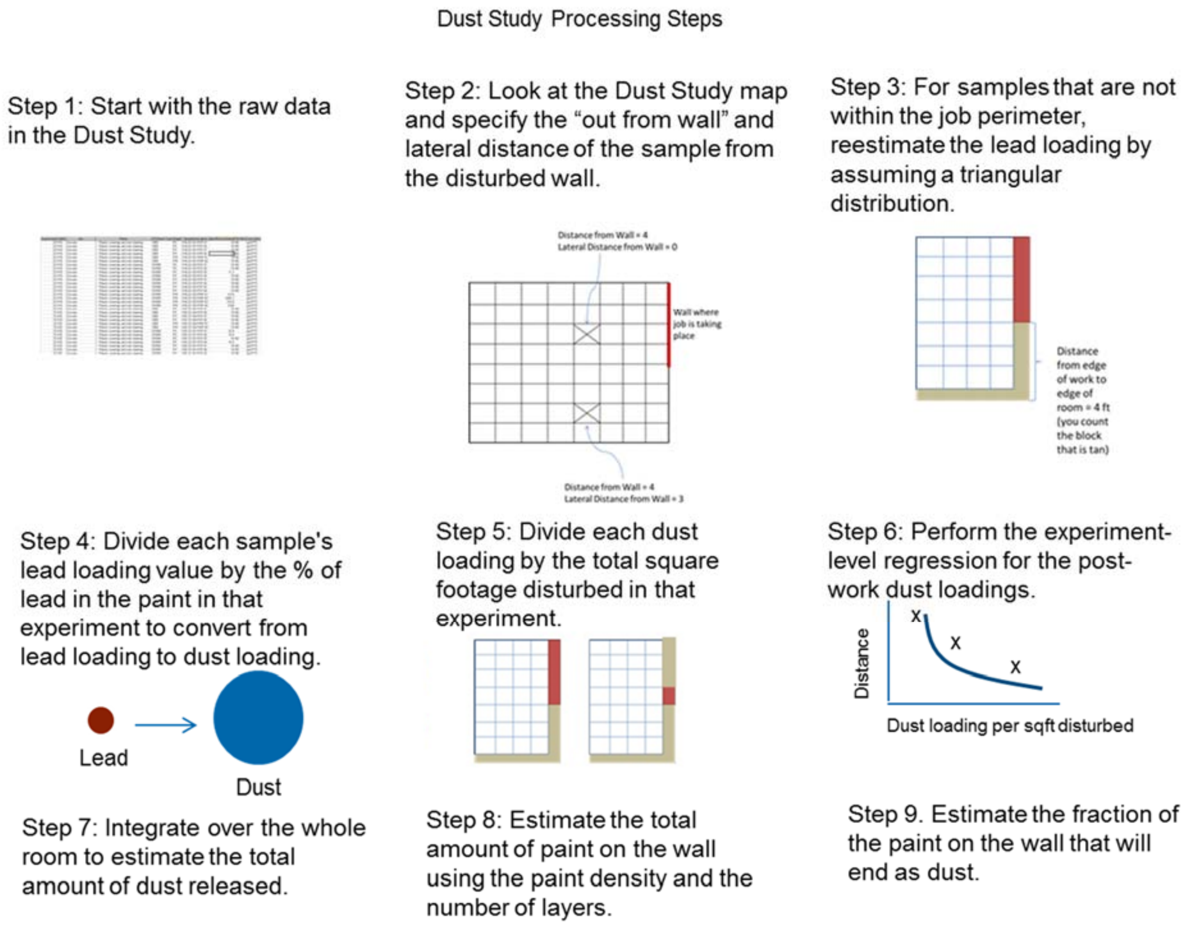
Both the *JobArea* and the *JobFloor Area* variables depend on assumptions about the size of the renovation job and the renovated room (a combination of the wall length and the wall length affected by the job). These variables are discussed in Appendix D.

As in the exterior analysis, the *DustFrac* is estimated using the Dust Study. This estimation process is described below in Section 4.2.1 and in detail in Appendix I.

4.2.1. Dust Study Processing

The Dust Study (US EPA 2007a) was a series of experiments that performed renovation activities in homes and schools with lead-based paint and then sampled the resulting floor lead loadings. Each experiment had differences in lead content in the paint, differences in job size, differences in job configuration, and differences in the crew performing the work. For this analysis, the Dust Study data were normalized to help account for these key differences before estimating an aggregate *DustFrac* value for each renovation activity type; this is referred to as "processing." The estimation of this variable is documented in Appendix I.

The processing steps for the Dust Study experiments are shown in Figure 4-3. Experiment maps were obtained from Battelle, the consulting firm that performed the Dust Study experiments. The maps indicated where the job and the sample trays were located in the room during the experiment.


Dust Study Processing Steps

Step 1: Start with the raw data in the Dust Study.

Step 2: Look at the Dust Study map and specify the "out from wall" and lateral distance of the sample from the disturbed wall.

Step 3: For samples that are not within the job perimeter, reestimate the lead loading by assuming a triangular distribution.

Step 4: Divide each sample's lead loading value by the % of lead in the paint in that experiment to convert from lead loading to dust loading.

Step 5: Divide each dust loading by the total square footage disturbed in that experiment.

Step 6: Perform the experiment-level regression for the post-work dust loadings.

Step 7: Integrate over the whole room to estimate the total amount of dust released.

Step 8: Estimate the total amount of paint on the wall using the paint density and the number of layers.

Step 9. Estimate the fraction of the paint on the wall that will end as dust.

Figure 4-3. Dust Study Processing Steps

To prepare the data and normalize for the confounding variables, the following steps were performed:

- Step 1: Organized raw Dust Study data (non-bulk samples) by experiment.
- Step 2: The distance from the job wall to the lead sample was estimated based on the provided experiment map.
- Step 3: If the dust loading sample was not taken from directly in front of the job wall (i.e., it was displaced to the side), the data were corrected to approximate what the loading would have been if the sample had been taken from directly in front of the wall.
- Step 4: Then, the lead loading was divided by the average percent of lead in the paint to estimate the dust loading on the floor (rather than the lead loading).
- Step 5: The dust loadings were divided by the total job area to estimate what the loading would have been if only 1 ft^2 had been disturbed.
- Step 6: After the loading data were normalized, a regression equation was fit to the adjusted loadings as a function of distance from the wall, assuming an exponential functional relationship.
- Step 7: Using the dimension of the room and integrating these regression equations, the total dust loading in the room after the renovation was estimated.
- Step 8: When the distances could not be used to derive regression equations, the room-average dust loading was multiplied by the floor area. The original amount of paint on the wall at the start of the experiment was estimated based on the vintage of the building.
- Step 9: The ratio between the amount of dust on the floor and the amount of paint on the wall was estimated.

This final ratio provided an estimate of the *DustFrac* variable for each of the 60 interior experiments. To obtain a single representative estimate for each renovation activity type (e.g., dry scraping or cabinet removal), the estimates for a given job type were then aggregated by taking the geometric mean across the relevant experiments. For two renovation activities, the fraction of paint that became dust was different enough within the activity to justify creating subcategories: window replacement with and without a saw and removal of paint via heat gun with a plaster and a nonplaster substrate.

4.2.2. Other Data Sources Considered

The Dust Study provides information for 60 interior experiments across different renovation activity types. To increase statistical power and potentially more robustly characterize the post-renovation dust loadings, other sources of data also were considered. A literature search was performed to find literature that provided:

- Loading or air concentration data specifically collected during or after a renovation event, and
- The necessary additional variables so that the experiment could be properly normalized by lead content, job size, and room size to estimate the *DustFrac* variable.

Both indoor air concentration and dust loading data were considered. The following equation was used to estimate the dust loading after the renovation based on the air concentration during the renovation:

$$FloorLoad \approx AirConc \times DepRate \times ExpDuration \times CeilingHeight \times UnitConv$$

Where:

FloorLoad = the floor lead loading after the experiment ($\mu g/ft^2$)

AirConc = the average air concentration during the renovation activity ($\mu g/m^3$)

DepRate = the particle deposition rate (h^{-1})

ExpDuration = the duration of the experiment (h)

CeilingHeight = the ceiling height in the room (m)

UnitConv = unit conversion to convert m^2 to ft^2

The deposition rate and duration were expected to vary by renovation activity. This approach was used to incorporate additional data on cleaning efficiency of interior control options into the analysis, and the results are further described in Appendix D (Grinshpun et al., 2002).

The studies shown in Table 4-2 were reviewed and provide exposure information for lead interior renovation activities in a wide variety of buildings. These results were not, however, added to existing Dust Study measurements to estimate *DustFrac.* Specifically, with the exception of the Grinshpun et al. (2002) data source, few of the other data sources identified included all of the information needed to estimate *DustFrac* by converting air concentrations to dust loading, (as described above with the Dust Study experiments). Approximating the additional values required for this analysis would introduce additional uncertainty, and for this reason, data from these alternative sources were not included in the modeling. Table 4-2 provides an overview of the data sources located. EPA also has requested additional data from other federal agencies, the construction industry, and the public that could be incorporated into the Approach. EPA, however, did not receive appropriate types of data or contextualizing information as described below.

- The type of renovation activity being performed.
- Total duration of the activity (length of time renovation activity was actually taking place).
- Sampling periods for air lead concentrations and descriptions of the task(s) performed during that sampling period (during renovation, immediately after renovation, both).
- Type and location of the air sample (personal breathing zone or area air sample for primary or bystander workers, next to the job in the renovated room, in the center of the renovated room, in an adjacent room, etc.).

- Location (floor, sill, or other surface of the renovated room or an adjacent room) and time when the wipe sample was collected (before, during, after renovation activity, or after clean-up activities).
- Size of the renovation job including total area (ft^2) of wall (or other building component) disturbed during the renovation.
- Description of the type of building and room being renovated, including the height of the ceiling in the renovation room and the square footage of the room.
- Measurements of the amount of lead in the paint.

Table 4-2. Other Data Sources Considered for Interior Dust Loading Estimation

Study	Data Type	Air Sampling Time and Duration of Activity	Size of Job and Size of Work Room	Lead Content in the Paint
Jacobs et al. (1998)	Air concentrations	✓	X	X
Lange et al. (2000)	Air concentrations	X	X	✓
NAHB (2006)	Lead loadings on floors and air concentrations	✓	X	X
Sussell et al. (1999) (previous NIOSH HHEs)	Lead loadings on floors and air concentrations	✓	X	✓
Sussell et al. (1998) (previous NIOSH HHEs)	Air concentrations	✓	X	✓
NIOSH (2000)	Air concentrations	✓	X	✓
NIOSH (2005)	Lead loadings on floors and air concentrations	✓	X	✓
OSHA Site Visit Data	Air concentrations	✓	X	✓
Reames et al. (2001)	Air concentrations	✓	X	X
Schirmer et al. (2012	Air concentrations	X	X	✓
Verma (2003)	Air concentrations	✓	X	X
US EPA (1997) (Environmental Field Sampling Survey)	Lead loadings on floors and air concentrations	✓	X	✓
Zhu et al. (2012)	Air concentrations	✓	X	✓

✓=yes and X=no

4.2.3. Dust Time Series

As mentioned at the beginning of Section 2, the interior analysis has three phases:

- The **dust-generating phase**, when the portion of the renovation job expected to generate lead-containing dust is performed. Any contractor cleaning occurs after the dust-generating phase.
- The **rest-of-renovation phase**, when the remainder of the renovation takes place.
- The **routine-cleaning phase**, when the renovation is complete and the dust levels are returning to background levels due to routine cleaning in the building.

The Dust Study data (US EPA 2007a) were used to estimate the average work room loading during the dust-generating phase ("post-work" in the Dust Study) and during the rest-of-renovation phase ("post-cleaning" in the Dust Study) using experiments where cleaning consisted only of dry-sweep cleaning. Comparisons between these loadings were used to estimate a phase factor so that the loading during the rest-of-renovation phase could be estimated from the simulated dust-generating phase using the equation:

$$WorkFloorLoad_{Rest} = WorkFloorLoad_{DustGen} \times PhaseFactor$$

Where:

$WorkFloorLoad_{Rest}$ = the work room floor lead loading during the rest-of-renovation phase ($\mu g/ft^2$)

$WorkFloorLoad_{DustGen}$ = the work room floor lead loading during the dust-generating phase ($\mu g/ft^2$)

$PhaseFactor$ = a factor applied to the work room dust-generating loading to estimate the corresponding rest-of-renovation loading

In addition to the post-renovation work room loading, EPA also estimated loadings in the rooms directly adjacent to the work room. The Dust Study captured data in "Observation Rooms" located near the work room (US EPA 2007a). The average dust levels from observation rooms in the Dust Study experiments were compared with the corresponding average work room loadings to estimate an adjacent factor such that:

$$AdjFloorLoad = WorkFloorLoad \times AdjFactor$$

Where:

$AdjFloorLoad$ = the floor lead loading during and after the renovation in the adjacent room ($\mu g/ft^2$)

$WorkFloorLoad$ = the floor lead loading during the renovation in the work room ($\mu g/ft^2$)

AdjFactor = a factor applied to the work room loading to estimate the corresponding adjacent room loading

Then, the routine cleaning phase time series was estimated by applying both a cleaning frequency and a cleaning efficiency to the room. Cleaning frequency was assumed to vary from once every working day to once every four weeks (see Appendix D). Then, on days when cleaning occurs,

$$FloorLoad_{New} = FloorLoad_{Old} \times CleanEff$$

Where:

$FloorLoad_{New}$ = the floor lead loading just after the current cleaning ($\mu g/ft^2$)

$FloorLoad_{Old}$ = the floor lead loading just before the current cleaning ($\mu g/ft^2$)

CleanEff = the cleaning efficiency

The routine cleaning continues until the room lead loading returns to pre-renovation background levels. This same cleaning equation was applied in both the work room and the adjacent room in each scenario.

4.2.4. Location of the Exposed Individual

The location of the exposed individual within the renovated building is an important and sensitive variable within the Approach. This variable affects the duration and magnitude of exposure based on how much time an individual spends in various locations within a building. A wide range of combinations are described below and further explored in the sensitivity analysis in Section 8.5.1. A subset of these combinations was modeled in the Approach.

As described in the beginning of Section 4 and in Figure 4-1, individuals can be located:

1. Inside the work area of renovated rooms (work area),
2. Outside the work area of renovated rooms (work room),
3. In rooms adjacent to renovated rooms (adjacent room), and
4. In other parts of the building where exposure is assumed to be at background levels (other).

And, based on whether the individual is allowed in the work area, work room, or adjacent room during the renovation, exposure to an individual could start at the:

1. Beginning of the dust-generation phase,
2. Beginning of the rest-of-renovation phase, or
3. Beginning of the routine cleaning phase.

Finally, individuals might spend their time:

1. In only one location in a building (one location), or
2. In both a primary location and other locations within the building (multiple locations).

The full list of potential exposure scenarios when individuals are confined to one location is shown in

Table 4-3. Several different combinations are possible when individuals move through the building and occupy multiple locations; these combinations are not listed because of the numerous possibilities, but several cases that assume the individual is present in two distinct locations were explored in the sensitivity analysis. Occupants included in the Approach were individuals who were located:

- In the work area, with exposure starting at the beginning of the dust-generating phase (Case 1),
- In the work room (but outside the work area), with exposure starting at the beginning of the dust-generating phase (Case 3),
- In the work area/work room, with exposure starting at the routine-cleaning phase (Case 5), and
- In an adjacent room, with exposure starting at the beginning of the dust-generating phase (Case 6).

Dust loadings were estimated for each occupant location in a particular renovated building scenario. Additional information on which combination is most likely to least likely to occur and is representative of various types of individuals who spend time in P&CBs will need to be determined in the future.

Table 4-3. Locations of Individuals and Timing of Exposure

Case	Number of Building Locations	Room	Present during dust-generation?	Present during rest of renovation?	Present during routine cleaning?	Included in Approach?
Case 1. One Location, Work Area, Always Allowed in Room During Renovation	One Location	Work Area	Yes	Yes	Yes	Approach
Case 2. One Location, Work Area, Partially Allowed in Room During Renovation	One Location	Work Area	No	Yes	Yes	Sensitivity
Case 3. One Location, Work Room, Always Allowed in Room During Renovation	One Location	Work Room	Yes	Yes	Yes	Approach
Case 4. One Location, Work Room, Partially Allowed in Room During Renovation	One Location	Work Room	No	Yes	Yes	Sensitivity
Case 5. One Location, Work Area, Not Allowed in Room During Renovation	One Location	Work Area/Work Room	No	No	Yes	Approach
Case 6. One Location, Adjacent Room, Always Allowed in Room During Renovation	One Location	Adjacent Room	Yes	Yes	Yes	Approach
Case 7. One Location, Adjacent Room, Partially Allowed in Room During Renovation	One Location	Adjacent Room	No	Yes	Yes	Sensitivity
Case 8. One Location, Adjacent Room, Not Allowed in Room During Renovation	One Location	Adjacent Room	No	No	Yes	Sensitivity
Case 9. One Location, Other Room	One Location	Other Room	No	No	No	No Exposure
Multiple Cases. Multiple Locations	Multiple Locations	Various	Various	Various	Various	Sensitivity

4.3. Work Practice/Control Options

Information on the efficiency of interior work practice/control options is presented below. EPA will consider the extent to which the work practice/control options are used during typical renovation jobs to determine which, if any are baseline practices and which are potential control options.

- One time contractor cleaning – broom sweeping
- HEPA vacuuming
- Wet mop cleaning with verification

- Use of horizontal plastic in the work room
- Use of vertical plastic as a barrier to the spread of dust to the rest of the building
- Local exhaust ventilation on equipment
- Replacement of higher emitting activities with lower emitting activities

Each control practice is associated with an efficiency that reduces the lead loading either after the renovation in the work room (e.g., horizontal plastic or wet mop cleaning with verification) or during and after the renovation in adjacent rooms (e.g., vertical plastic). So, for a particular control option,

$$FloorLoad = FloorLoad_{Base} \times ControlFactor$$

Where:

$FloorLoad$ = the floor lead loading in the Dust Study “post-cleaning phase” after cleaning has occurred or plastic has been removed ($\mu g/ft^2$)

$FloorLoad_{Base}$ = the floor lead during the Dust Study “post-work phase,” before cleaning has occurred or plastic has been removed ($\mu g/ft^2$)

$ControlFactor$ = a factor applied to the post-work loading to estimate the corresponding control option loading.

Factors were developed for the different control option combinations shown in Table 4-4.

Table 4-4. Control Option Combinations Considered in the Approach

Control Option	To Which Room Loading is the Factor Applied?	Efficiency
Dry sweeping only	Work	0.943
Horizontal Floor Plastic with Dry Sweeping	Work	0.956
Wet Mop Verification Cleaning	Work	0.975
Horizontal Floor Plastic and Wet Mop Verification Cleaning	Work	0.993

4.4. Contributions from Exterior Renovations and Track-in to Renovated Building

The loadings in the different rooms inside the renovated P&CB depend on the renovation activities inside the renovated building; however, if the building exterior is also renovated, occupants could track in lead-containing soil and further increase the interior lead loadings. In addition, elevated air concentrations during the exterior renovation could penetrate the building shell and lead to elevated interior lead floor loadings.

For any given renovated building, the outdoor soil concentration could be at background (no significant renovation event on exterior of building) or any number of renovation-related elevated concentrations. The frequency of exterior and interior renovation activities occurring at the same time is expected to be low. To account for this exposure pathway when it does occur, three exterior soil concentrations were chosen, as shown in Table 4-5.

Table 4-5. Low and High Dust and Soil Levels from Track-in to Same P&CB

Control Option	Soil μg/g
Background levels	n/a
"Low" exterior renovation scenario	3.9
"High" exterior renovation scenario	27.5

The exterior scenarios provide estimates of the mean receptor building-level outdoor soil levels resulting from a given exterior renovation. The low and high scenarios were selected from the full set of exterior scenario results by choosing the 25th and 75th percentiles for commercial and school receptor buildings. Thus, to include the exterior renovation contribution to the interior of the renovated building, each iteration in the Monte Carlo modeled sampled regardless of whether an exterior renovation job was also present. Then, in the high and low cases, the mean soil levels for the closest exterior receptor building in the background, low, and high exterior scenarios were selected for use in the interior model; a track-in term was added to the dust time series to account for the track-in from these exterior jobs.

5. Selection and Update of the Leggett Model

The Leggett blood lead model was selected as the primary blood lead model for the Approach (Leggett 1993). Leggett model intake rates can be varied daily or weekly, enabling the model to capture intermittent, short-term exposure scenarios, such as renovation activities, more accurately than models that can vary intakes only monthly (e.g., the IEUBK model). The model also can be parameterized for both children and adults, unlike other models such as IEUBK. The Leggett blood lead model was selected as the primary blood lead model for the 2008 LRRP Technical Approach for Residences, and this decision was supported by the 2008 LRRP Clean Air Science Advisory Committee (CASAC) panel (EPA 2007c).

EPA considered daily, weekly, biweekly, and monthly periods over which to average both background and renovation-related exposures in the Leggett model. Exposures to lead involve a mix of long-term exposures at relatively constant concentrations and possible intermittent short-term exposures at higher concentrations. Blood lead estimates vary over time in response to these different kinds of exposures. One study used the Leggett model to evaluate model averaging times and suggests that use of averaging times that exceed the shortest exposure duration characterizing intermittent exposures introduces uncertainty into model estimates (Lorenzana et al., 1998). EPA selected a biweekly period for pre-renovation exposure levels and a weekly period for renovation levels until blood lead returned to background. The dust-generating phase of exterior renovations, on average, were estimated to last approximately 1 week. The dust-generating phase of interior renovations, on average, were estimated to last approximately 3 weeks. Using a daily averaging time for renovation activities lasting less than 1 week could potentially improve model estimates, but does add significant time to model runs.

Prior to implementing the Leggett model, several updates were made to the 1993 model based on recent literature and data availability. In particular,

- Red blood cell volume, plasma volume, and skeletal and kidney masses were scaled to appropriate values for small children through adolescents;
- Several measures of bone mineral transfer rates were evaluated and updated from those of the 1993 model;
- The nonlinear red blood cell saturation level was revised to yield a linear model; and
- The model was evaluated and calibrated using NHANES data (children) and serial bone and blood lead measurements in an occupational population of 209 lead smelters (Nie et al., 2005), as described in Appendix M.

The model updates and testing are fully described in Appendix M.

Previous comparisons using the older Leggett model have shown that, under chronic exposure conditions, the blood lead estimates obtained with the Leggett model are approximately two to three times higher than those obtained with the IEUBK model (Pounds and Leggett 1998). These results suggested that short-term exposures in the Leggett model might be overestimated, and that lead uptake levels to give selected blood lead levels might be underestimated. These issues are no longer the case with the updated Leggett model, as shown in Appendix M, Figure M-4.

The Leggett model does not include an exposure model and thus does not accept exposure concentrations directly. Instead, the model uses total inhalation and ingestion intakes (administered doses) as inputs. Thus, the exposure concentration time series are converted to intakes using intake parameter inputs. To obtain estimates of blood lead, both the time series of the media inputs (air, indoor dust, and outdoor soil) and the age-specific exposure factor values that govern intake and absorption processes must be specified. These intake values are described further in Appendix N.

6. Estimating Health Effects in Children and Adults

After simulating the blood lead changes associated with each renovation activity, concentration-response functions were used to relate the incremental blood lead change to an associated health effect in children and adults. The following section describes how the health effects were chosen, which

Leggett blood lead model metric can be related most appropriately to the available health effects literature, and how the concentration-response functions were characterized. Further details for each concentration-response function characterization can be found in Appendix P.

6.1. Selection of Health Effects

Many health outcomes were considered for this analysis. The *Integrated Science Assessment (ISA) for Lead* (US EPA 2013) and the National Toxicology Program (NTP) *Monograph on Health Effects of Low-Level Lead* (NTP 2012) were evaluated, and those effects reported to be “causal,” “suggestive,” or “likely causal” in the ISA and “sufficient evidence of an association’" in the NTP report were considered for this analysis. A weight-of-evidence approach was used to consider which health effects might be appropriate for this analysis. The health effects on the following systems were selected for consideration: nervous system, renal, reproductive and developmental, cardiovascular, immune, and hematologic effects. The studies associated with each effect were evaluated based on the strength of the association, whether a concentration-response function was provided, the levels of exposure relevant to current population exposures, and the biological significance of the effect.

Both adults and children were considered in this analysis. For children, cognitive function as measured by IQ met the above criteria. IQ is one of the most sensitive endpoints for children and it was also used in the 2008 LRRP analysis for residences (US EPA 2008). The health effects selected for adults based on these criteria were low birth weight, cardiovascular disease mortality (CVDM), and decreased kidney function (glomerular filtration rate [GFR] < 60). Short descriptions of the studies are provided below, but detailed analyses can be found in the ISA for Lead (US EPA 2013).

The development of a concentration-response function for adult health effects is complicated by the lack of knowledge of whether the health effect is actually related to current blood lead levels or the result of higher blood lead levels at earlier times in life. In the United States, exposures to lead were much higher before lead was removed from gasoline and consumer paints. Blood lead levels in the 1970s were around 40 µg/dL and could have been as high as 60 µg/dL in the 1960s (Smith and Flegal 1992). According to NHANES, blood lead levels continue to decline each reporting period (CDC 2013). From 1999 to 2010, adult blood lead levels (20 years and older) decreased 30 percent, and blood lead levels of young children (1–5 years old) decreased 48 percent. The geometric mean blood lead levels reported in NHANES 2009–2010 for all ages was 1.12 µg/dL (1.17 µg/dL for children 1–5 years and 1.23 µg/dL for adults). This reporting period (2009–2010) was the first where the geometric mean adult blood lead levels have exceeded (albeit by a small increment) those in young children. Typical blood lead levels in 2009–2010 were less than 1 µg/dL in children 6–19 years of age (geometric mean 0.84 µg/dL for 6–11 years and 0.68 µg/dL for 12–17 years). The blood lead level of the 95th percentile was 3.37 µg/dL for children (1–5 years) and 3.57 µg/dL for adults. Generally, adults—and particularly older adults—had much higher exposure to lead in the past. Blood lead levels in 2014 might or might not continue to reflect past trends, leading to possible lower blood lead levels today than those reported in 2009–2010.

6.2. Selection of Lead Model Metric

The exposure scenario is an important consideration when analyzing the health outcomes that could be used for this Approach. Both blood lead and, more recently, bone lead measures have been used as biomarkers of exposure for lead in epidemiology studies. Blood lead reflects recent exposure history. The half-life of blood lead is approximately 30 days (Graziano 1994). In children, blood lead provides a reasonable measure of recent exposure and possibly lifetime body burden because the exchange between bone and blood lead is faster in children than in adults. On the other hand, the half-life of bone lead, depending on which bones are considered, is years to decades. Skeletal lead represents the vast majority of lead body burden in adults and because of lead's long residence time in bone (particularly in the tibia), measurement of bone lead is an estimate of lifetime cumulative lead dose (US EPA 2013). Bone can release its lead content into the bloodstream in the course of normal bone metabolism and might release lead at increased rates during active bone demineralization in later life and during pregnancy. The contribution of bone lead to blood lead changes depending on the duration and intensity of the exposure, age, and various other physiological stressors (e.g., nutritional status, pregnancy, menopause, extended bed rest, hyperparathyroidism) that can affect bone remodeling, which normally and continuously occurs. Through release of lead from bone, adult bone lead can maintain lead levels in blood long after external exposure has ceased (US EPA 2013).

The exposure scenario being modeled for renovation activities for P&CBs is a short-term increase in exposure during the dust generating phase of the renovation. After the dust generation ceases, blood lead levels from renovation activities will decline rapidly over the first few months and then there will be a gradual, slow decline in blood lead concentrations over the next several years (US EPA 2013). Therefore, the contribution of the exposure from short term LRRP activities would be better characterized by blood lead levels. The contribution of a short-term exposure to a health effect that is exerted chronically is unknown. A single renovation activity will result in a short burst of exposure which will be reflected in blood lead but will likely not be reflected in bone lead during the exposure renovation period. For these reasons, blood lead was chosen as the appropriate metric for use in assessing the health effects data for use in the Approach.

6.3. Concentration-Response Characterization for IQ in Children

Section 4.3.11 of EPA's ISA for Lead reports that epidemiologic studies consistently show that blood lead levels measured during various lifestages or periods throughout childhood, as well as averaged over multiple years during childhood, are associated with cognitive function decrements (US EPA 2013). An international pooled analysis of seven prospective studies (Boston, MA; Cincinnati, OH; Rochester, NY; Cleveland, OH; Mexico City, Mexico; Port Pirie, Australia; and Kosovo, Yugoslavia) and individual-level data from 1,333 children aged 4.8–10 years with a median concurrent blood lead level of 9.7 µg/dL, found that increments in concurrent and peak blood lead levels were associated with a decrease in full-scale IQ (intelligence quotient [FSIQ]), hereafter referred to as IQ (Lanphear et al., 2005). The pooled analysis demonstrated a blood lead-associated decrement in IQ in a diverse population with application of a uniform statistical model across cohorts.

In the Lanphear et al. (2005) study, IQ was assessed at school age (mean age at IQ testing was 6.9 years). All children were assessed with an age-appropriate version of the Wechsler scales. Four measures of lead exposure were examined: concurrent blood lead (blood lead level closest in time before the IQ test), maximum blood lead level (peak blood lead measured at any time prior to the IQ test), average lifetime blood lead (mean blood lead from 6 months to the concurrent blood lead test), and early childhood blood lead (mean blood lead from 6 to 24 months). A pooled analysis of the relationship between cord blood lead levels and IQ also was conducted in the subsample for which cord blood lead tests were available.

Lanphear et al. explored regression models that adjusted for the effect of blood lead for study site, maternal IQ, the home observation measurement for the environment (HOME) score (providing an assessment of the stimulation and support available to a child at home), birth weight, and maternal education. Statistical testing was used to assess the linearity or nonlinearity of the relationship between blood lead levels and IQ. Regression diagnostics also were performed to ascertain whether lead coefficients were affected by colinearity or influential observations. The fits of all four measures of postnatal blood lead levels were compared based on R^2 values. The blood lead measure with the largest R^2 (adjusted for the same covariates) was nominated *a priori* as the preferred blood lead index relating lead exposure to IQ in subsequent inspections of the relationships. The primary analysis used a fixed-effects model, although a mixed model treating sites as random effects was also examined.

The median lifetime average blood lead concentration was 12.4 µg/dL (5th to 95th percentile, 4.1 to 34.8 µg/dL) with about 18 percent of the children having peak blood lead levels less than 10 µg/dL. The 5th- to 95th-percentile concurrent blood lead levels ranged from 2.4 to 30 µg/dL. The mean IQ of all children was 93.2 (SD=19.2) but this varied greatly between studies. All four measures of postnatal exposure were highly correlated with IQ. The concurrent blood lead level, however, exhibited the strongest relationship with IQ, as assessed by R^2. Nevertheless, the results of the regression analyses for all blood lead measures were very similar. The best-fitting model included the log of concurrent blood lead, study site, maternal IQ, HOME Inventory scores, birth weight, and maternal education.

Various models, including a linear model, a cubic spline function, a log-linear model, and a piecewise linear model, were investigated in Lanphear et al. (2005). The shape of the concentration-response relationship was determined to be non-linear; the log-linear model was found to best fit to the data, based on R^2 values. Using the log-linear models, the authors estimated a decrement of 1.9 points (95% CI: 1.2, 2.6) in IQ for a doubling of concurrent blood lead. Thus, the IQ point decrements associated with an increase in blood lead from less than 1 to 10 µg/dL compared to 10 to 20 µg/dL were 6.2 points (95% CI: 3.8, 8.6) versus 1.9 points (95% CI: 1.2, 2.6). The individual effect estimates for the seven studies used in the pooled analysis also generally indicate steeper slopes in studies with lower blood lead levels compared to those with higher blood lead.

Budtz-Jørgensen et al. (2013) reanalyzed the Lanphear et al. data using linear mixed models and derived a benchmark dose (BMD) estimate and a lower 95 percent confidence limit on the BMD for the effects of childhood blood lead on IQ. Appendix P provides a more detailed discussion of Budtz-Jørgensen et al. (2013) reanalysis of data from the Lanphear et al. (2005) pooled study. After reviewing this reanalysis, EPA chose to maintain the basic regression approach to estimating blood lead impacts on IQ originally described in the Lanphear et al. (2005) publication.

Crump et al. (2013) also reanalyzed the Lanphear et al. (2005) data, correcting what they considered to be errors in blood lead reporting and IQ test results in the earlier analysis. They confirmed the basic findings of highly significant log-linear fits exactly reproduced Lanphear et al. (2005) findings using the original data, and updated the log-linear models using the "corrected" data (see Table 6-1). Among the changes made by Crump et al. was their use of the General Cognitive Index scores derived from tests administered simultaneously with blood lead measurements at 57 months of age to estimate the effects of concurrent exposures in the Boston (Bellinger et al., 1992) cohort. In the original analyses, Lanphear had used blood lead measurements at 57 months as the "concurrent" blood lead estimate with the results of Weshcler Intelligence Scale test administered at 120 months, a decision that Crump et al. (2013) did not find appropriate. Even with this change, however, the estimated regression coefficient and confidence limits for the impact of concurrent blood lead on IQ changed only minimally (Table 6-1) The recalculated coefficient (−2.65) and 95 percent upper and lower confidence limits (−1.61, −3.69) are therefore used in the Monte Carlo simulation of IQ impacts based on concurrent blood lead. Similarly, Crump et al. (2013) estimated a coefficient (−3.19) and confidence limits (−4.45, −1.94) for lifetime blood lead that was not significantly different from that originally estimated by Lanphear et al. (2005).

Table 6-1. Log-linear Blood-lead IQ Coefficients and Confidence Intervals Derived by Crump et al. (2013) Based on Original and Corrected Data from Lanphear et al. (2005)

Blood Lead Metric	Reproduced Using Original Data	Results Using Corrected Data
Early Life	−2.04 (−3.27, −0.81)	−2.21 (−3.38, −1.03)
Peak	−2.85 (−4.1, −1.6)	−2.86 (−4.10, −1.61)
Lifetime	−3.04 (−4.33, −1.75)	**−3.19 (−4.45, −1.94)** [a]
Concurrent	−2.70 (−3.74, −1.66)	**−2.65 (−3.69, −1.61)**[a]

[a]These values are used in the Approach

Based on the above analyses, EPA chose to estimate IQ reduction based on both concurrent and lifetime average blood lead concentrations. In the Lanphear et al. study, "concurrent" refers to the blood lead measured closest to the administration of the IQ test. However, in the context of this Approach, "concurrent" is not used in the same context and instead refers to a point estimate of blood lead at a given time point after the renovation. Based on the Lanphear et al. (2005) and Crump et al. (2013) studies, both metrics were found to be significantly correlated with measured IQ. For concurrent blood lead, the Monte Carlo analysis estimated potential IQ lost based on a single "measurement" (simulated blood lead concentration) a predetermined (simulated) time after renovation, and IQ loss was estimated based on the regression coefficient from the Lanphear/Crump log linear model for concurrent blood lead (see below). Lifetime average blood lead was estimated in EPA's modeling based on the time-weighted average blood concentrations from birth until blood lead returns to background as simulated by the Leggett model, and the lifetime average regression coefficients were used to estimate potential IQ loss.

Log-linear models were used in preference to the piecewise linear models because (1) they provide better qualitative fits across the range of blood lead being investigated (e.g., the log-linear model appeared to more closely follow the trend in the data than the piecewise model); and (2) incorporating uncertainty in the log-linear models into the IQ estimate process is more straightforward than for the piecewise models. Lanphear et al. (2005) found that the log-linear model provided excellent fits to the data relating blood lead metrics and IQ in the pooled data (see previous discussion.) The form of this equation is:

$$FSIQ = \alpha + \beta_0 * \ln(\text{blood lead}+1) + \beta_1 * X_1 + \beta_2 * X_2 + \ldots + \varepsilon,$$

Where:

α = the model intercept

β_0 = the coefficient for (log) blood lead

β_1, β_2, etc. = the coefficients for covariates (study site, maternal IQ, HOME Inventory, birth weight, and maternal education), and

ε = the normally distributed residual term.

This model form explains a large proportion of the variance for all the blood lead metrics used ($0.62<R^2 < 0.63$), and the β coefficients for all four blood lead metrics (early life, concurrent, peak, and lifetime) were highly significant and negative.

As mentioned above, the median blood lead in the Lanphear et al. (2005) pooled data set was 9.7 µg/dL, significantly higher than current background blood lead levels among U.S. children. The current background values are, according to NHANES, on the order of 1 µg/dL. Despite the relatively high median value, the Approach used equations based on the Lanphear et al. (2005) pooled analysis because a sufficient number of children had blood leads in the range 1−5 µg/dL to support the model fit in this range (see Crump et al. (2013) Figure 2).

Monte Carlo estimation of the changes in IQ associated with renovation were conducted for each individual "sampled" in the simulation using both the concurrent and lifetime average metrics. Blood lead "measurements" (outputs from the Leggett model) were generated for a given individual under background exposure conditions (with variability determined by sampling from exposure-associated input variables) and under identical conditions except that the blood lead measurement was also affected by a renovation at some time prior to the measurement. Change in IQ was then estimated as:

$$\Delta IQ = \Delta \ln PbB + \beta * N(0, std. err.)$$

Where:

$$\Delta lnPbB = \ln(\frac{PbBrenovation}{PbBBackground})$$

The second term in the equation includes β, the regression coefficient from the concurrent and lifetime average blood lead regressions and a normally distributed variable characterized by mean 0 and standard error associated with the corresponding β estimate. As noted above, the β values for concurrent and lifetime blood lead were −2.65 and −3.19, respectively. The standard errors of β (0.53 for concurrent and 0.64 for lifetime average blood lead) were calculated from the 95 percent upper and lower confidence limits given in Table 6-1 using the normal approximation. Inclusion of this term accounts for statistical uncertainty associated with the estimate of the beta coefficient; it does not incorporate all sources of uncertainty in individual IQ responses to changes in blood lead.

IQ changes were not estimated for individuals with simulated post-renovation blood lead levels less than 1.0 μg/dL, similar to the 2008 LRRP analysis and in agreement with the range of measured blood leads in the Lanphear et al. (2005) pooled analysis. Less than 1 percent of the observations supporting the Lanphear et al. (2005) statistical models were below this value, and thus estimating IQ changes in this blood lead range was not justified. The overall output of the analysis is quantile estimates of IQ changes associated with renovation derived from the Monte Carlo samples for each renovation scenario.

6.4. Concentration-Response Characterization for Low Birth Weight

Multiple studies were reported in the ISA for Lead that examined the association between maternal blood lead and birth weight/fetal growth (US EPA 2013). The ISA considers the association between lead exposure and low birth weight (LBW) to be “suggestive of a causal” relationship. The associations were not always consistent across all studies considered in the ISA but a large retrospective study (n = 43,288) conducted in New York state from 2003 to 2005 showed that increased maternal blood lead was associated with decreased birth weight in infants (Zhu et al., 2010). This study provided data on low blood lead levels (mean blood lead level was 2.1 μg/dL), adjusted for many confounders, and measured a continuous birth weight instead of a dichotomous comparison of infants at/above and below 2500 g.

Mothers, aged 15–49 years with blood lead level less than 10 μg/dL (over 99 percent of participants) provided blood lead samples during pregnancy to the NY State Heavy Metals Registry. Included in this analysis were 2,744 low birth weight infants. Atomic spectrometry was used to determine blood lead levels and the detection limit for blood lead analysis was 1 μg/dL. Birth outcomes, including birth weight measured as a continuous variable, preterm birth defined as <37 weeks from date of last menstrual period, and small for gestational age (SGA) defined as birth weight below the 10th-percentile of birth weight for gestational age were obtained from birth certificates. Potential confounders controlled for in this analysis included maternal race and ethnicity, maternal age, maternal education, financial assistance participation, self-reported smoking during pregnancy, alcohol consumption during pregnancy, illicit drug use during pregnancy, trimester when prenatal care started, timing of lead sample, parity, sex of child, and pre-pregnancy body mass index (Zhu et al., 2010).

The rates of low birth weight for the cohort were 6.3 percent, 8.1 percent for preterm birth and 9.5 percent for SGA. Adjusted odds ratios (ORs) of blood lead levels were estimated from logistic regression with fractional polynomials. Adjusted ORs were not statistically significant for preterm birth and SGA. Changes in birth weight estimates varied with blood lead levels, with the greater decreases in birth weight occurring at the lower blood lead concentrations, without evidence of a threshold effect. Birth weight reduction was estimated using log-transformed blood lead in fractional polynomial regressions. The best fit was obtained when blood lead was expressed using a square root transformation. An estimated mean value of 27 g was reported for a 0- to 1-µg/dL change in blood lead with smaller reductions per µg/dL at higher blood lead concentrations (see Table 6-2). After exclusion of mothers with blood lead measurements less than 1 µg/dL, a linear model provided the best fit to the data, with a 1-µg/dL increase in blood lead associated with a 7.0-g decrease in birth weight (in the range 1–10 µg/dL) (Zhu et al., 2010).

Table 6-2. Predicted Birth Weight Reductions Based on Fractional Polynomial Model[1]

Maternal Blood Lead (µg/dL)	Predicted Body Weight Reductions (grams)	95% UCL	95% LCL
0	--	--	--
1	−27.4	−17.1	−37.8
2	−38.8	−24.1	−53.4
3	−47.5	−29.6	−65.4
4	−54.8	−34.2	−75.5
5	−61.3	−38.2	−84.4
6	−67.2	−41.8	−92.5
7	−72.5	−45.2	−99.9
8	−77.6	−48.3	−106.8
9	−82.3	−51.2	−113.3
10	−86.7	−54.0	−119.4

[1]Source: Zhu et al. (2010), Table 3
UCL = Upper Confidence Limit
LCL = Lower Confidence Limit

Changes in birth weight were estimated using the fractional polynomial (square-root) model that was determined by Zhu et al. (2010) to provide the best fit to the data. As in the case of IQ loss, background (non-renovation) and post-renovation blood lead concentrations were estimated for the same hypothetical individuals using the exposure models described in the preceding chapters, and the Leggett blood lead model. In this case, however, changes in blood lead were estimated for adult (18–49 year-old) women. Because of computational limitations, running a specific set of simulations using the probability distribution for pregnancy between ages 18 and 49 years was not feasible. Instead, the age distribution in the model was set equal to the general population distribution. The blood lead profile for women within this age range in the Leggett model is similar, however, so age does not play a significant role in determining the resulting estimated birth weight distribution.

For any maternal blood lead change, the reduction in birth weight predicted to be associated with renovation was estimated as:

$$\Delta BW = \Delta\sqrt{PbB} \times 27.4 + N(0, \Delta\sqrt{PbB} \times 5.78)$$

Where:

ΔBW = the predicted change in birth weight, and

$$\Delta\sqrt{PbB} = \sqrt{PbB_{Renovation}} - \sqrt{PbB_{Background}}$$

In the above equation, the value 27.4 equals the predicted birth weight reduction associated with a change of maternal blood lead from a (hypothetical) level of 0 μg/dL to 1 μg/dL. The changes in birth weight associated with further blood lead increments then scale as the square root of the increment between pre- and post-renovation blood lead levels. Similarly, 5.28 is the standard deviation of the predicted changes in birth weight, derived from the confidence limits shown in Table 6-2. The standard deviation likewise scales with the square root of increasing blood lead increment. As for IQ change, the notation N(0 , $\Delta\sqrt{PbB} \times 5.78$) indicates a random sample from the normal distribution with the indicated mean and standard deviation. This random sampling is done for each iteration within all Monte Carlo iterations and incorporates the variability in the estimated changes in birth weight, given a specified change in blood lead.

In estimating birth weight reductions, the relationship expressed in the above equation was limited to Monte Carlo subjects where the post-renovation blood lead value is estimated to be greater than 1.0 μg/dL. When the post-renovation blood lead was less than 1 μg/dL, the estimated birth weight reduction for that individual was estimated to be zero. This convention reflects the uncertainty in the data and model results below 1 μg/dL, the detection limit for blood lead values reported in the Zhu et al. (2010) study. Similarly, where background blood lead values were estimated to be less than 1.0 μg/dL, the values were adjusted to 1 μg/dL, again to restrict the estimation of birth weight reductions within the range of the data. To the extent that a substantial proportion of background concentrations are below 1.0, this adds an element of uncertainty to the model results. Although estimating the degree of uncertainty associated with the procedure is difficult, for any individual in the simulation with estimated blood lead below 1 μg/dL, the range of estimated birth weight reduction is bounded at the lower end by zero and at the upper end by approximately the estimated birth weight reduction for women with a blood lead level of 1 μg/dl (27.4 grams.)

In this analysis, EPA applied the C-R function for low birth weight to hypothetical individuals aged 18–49. The Zhu study included some participants 15–18 years of age, but the published paper does not include sufficient information about the number or characteristics of these women to support analysis for these women at this time. The paper reports that the minimum maternal age of the study participants was 15 and the 10th percentile was 20, of 43,288 participants for whom maternal age was known, but the number of women under the age of 18 is unknown. In addition, although a simple averaged effect of age was accounted for in the study, no analysis was reported that would control specifically for the well-established effect that young maternal age (ages 15–18, for example) has on birth weight. The birth weight effects reported are adjusted to be for a maternal age of 27.6 years, the average age in the study, but are not necessarily appropriate for underage mothers.

6.5. Concentration-Response Characterization for Kidney Function

Several studies have reported an association between reduced kidney function and blood lead levels less than 10 µg/dL (Lai et al., 2008; Hernandez-Serrato et al., 2006; Goswami et al., 2005). Lower estimated GFR is an indicator of chronic kidney disease. This endpoint was considered "suggestive of a causal" relationship in the ISA for Lead (US EPA, 2013). Two studies were considered for this analysis (Muntner et al., 2003; Navas-Acien et al., 2009) but ultimately Navas-Acien et al. (2009) was chosen to provide the C-R function. Both studies analyzed NHANES data but Muntner et al. (2003) used NHANES III data when blood lead levels were much higher than they are now.

Navas-Acien et al. (2009) analyzed NHANES 1999-2006, estimating relationships between reduced kidney function and blood lead and cadmium concentrations. The geometric mean blood lead level for lead was 1.58 µg/dL in 14,778 participants 20 years and older. Odds ratios were calculated for reduced estimated GFR (eGFR) (<60 mL/min/1.73m^2), albuminuria, a (≥30 mg/g creatinine) and for individuals having both symptoms simultaneously. Odds ratios were adjusted for socio-demographic factors (sex, race/ethnicity), as well as body mass index, education, smoking status, urinary cotinine , current and former alcohol intake, hypertension, and diabetes mellitus. Analyses were conducted for either lead or cadmium separately, and using models that included both.

Logistic regression was applied to estimate the ORs for reduced eGFR across blood lead quartiles in men, women, and in the entire cohort, using models with different degrees of adjustment. In addition, regression models were estimated that included blood lead and cadmium levels as continuous variables.

Blood lead and cadmium data were highly skewed, and both were log-transformed when entered in the regression models.

For the study cohort as a whole, the trend in fully adjusted ORs (estimated using "Model 3" from Navas-Acien et al. (2009), which contains all the covariates listed above) for reduced eGFR was highly significant across blood lead quartiles. Model 3 includes urinary cadmium as a covariate, so the resultant estimates quantify the relationship between reduced eGFR and blood lead levels, controlling for variations in cadmium exposure as well. Adjusted ORs for the second and third quartiles (1.10, 1.36) were elevated compared to the referent group, but not significantly at $\alpha=0.05$ (Table 6-3). The estimated OR for the fourth quartile (1.56) was significantly elevated. Adjusted ORs for albuminuria versus blood lead were not significantly elevated in the 2nd-4th quartiles compared to the reference group.

Table 6-3. Fully-Adjusted (Model 3) Odds Ratios for Reduced eGFR (Navas-Acien et al., 2009)

Quartile Blood Lead Range (median)	Odds Ratio for Reduced GFR (95 Percent Confidence Limits)	Odds Ratio for Albuminuria (95 Percent Confidence Limits)
< 1.1 (0.8)	1	1
1.1–1.6 (1.3)	1.1 (0.80–1.51)	0.83 (0.66–1.04)
1.6–2.4 (1.9)	1.36 (0.99–1.85)	0.92 (0.76–1.12)
> 2.4 (3.2)	1.56 (1.17–2.08)	1.19 (0.96–1.47)

Navas-Acien et al. also estimated relative risks of reduced eGFR based on the fully adjusted regression models that included (log) blood lead and cadmium as continuous variables. For the entire cohort, the estimated OR associated with an increase in blood lead from 1.1 to 2.4 μg/dL (the 25th–75th percentiles of the observed values) was 1.31 with 95 percent confidence limits of 1.16 and 1.47 (Table 6-4). The estimated OR was higher in women (1.44) than in men (1.13), and the latter value was not significantly different from 1.

Table 6-4. Odds Ratios for Reduced eGFR Associated with an Increase in Blood Lead Concentration from 1.1 to 2.4 μg/dL

Group	Odds Ratio for Change in Blood lead from 1.1–2.4 μg/dL (95% confidence intervals)
Men	1.13 (0.96–1.33)
Women	1.44 (1.22–1.69)
Men + Women	1.31 (1.16–1.47)

Because the concentration-response for albuminuria was found to be not statistically significant, EPA has chosen the blood-lead to reduced eGFR relationship as the endpoint for the simulation. As discussed below, gender-specific ORs and changes in prevalence will be estimated based on the regression models shown in Table 6-4.

In the Approach, the marginal increase in the prevalence of reduced GFR was calculated based on the regression results presented by Navas-Acien et al. (2009). Estimated ORs from the simulation were multiplied by gender- and age-specific background prevalence estimates for category 3-5 kidney disease for the U.S. population. As for the other endpoints, marginal risks were calculated based on the difference in blood lead levels seen in the same (simulated) individual experiencing background and renovation exposures. The absolute risk of an individual of a given sex and age having low eGFR was estimated using the following equation:

$$\mathrm{LGFR} = \mathrm{LGFR}_0{*}\mathrm{e}^{(\beta + \varepsilon)^{*}\Delta\,\mathrm{lnPbB}} LGR = LGFR_0 * e^{(\beta+\varepsilon)*\Delta lnPbB}$$

$$\Delta lnPbB = \ln((PbB_{Renovation})\,/(PbB_{Background}))$$

Where:

LGFR₀ = national background prevalence of reduced GFR for an individual of a given age and gender catalogued by the Centers for Disease Control and Prevention (CDC) (http://nccd.cdc.gov/CKD/default.aspxhttp://nccd.cdc.gov/CKD/default.aspx)

β = the gender-specific regression coefficient for reduced GFR derived from the data presented in Table 6-4

ε = the normally distributed variable representing the uncertainty in the β coefficient (calculated as described in Appendix P.5.1)

As the model is formulated in the above equation, the extra risk of reduced eGFR for a given individual is LGFR - LGFR_0. The exponential term in the equation above represents the OR for the exposed individual. In cases where the background incidence of the health outcome is low, the OR serves as an approximation for the risk ratio. In this case, because low GFR is a relatively rare outcome, the concentration response function estimates the risk ratio of reduced GFR as a function of both concurrent and lifetime average blood lead concentrations. (See Section 7.3.2 for more discussion of the concurrent and lifetime average approaches.)

The 1999–2006 NHANES data used by Navas-Acien et al. (2009) included blood lead measurements at detection limits as low as 0.25 μg/L, considerably lower than the detection limits in the other studies that provided data for this Approach document. Little information was provided regarding potential blood-lead to reduced GFR relationship in the lower portion of the cohort; the first quartile, which has a median blood lead level of 0.8 μg/dL, was used as a reference group against which the other quartiles were evaluated. Although the regression analysis with blood lead as a continuous variable included the entire data set down to the detection limits, much uncertainty is associated with the application of the regression in that range. Thus, in this analysis, relative risks of 1.0 were assigned to any individual having a renovation-related blood lead level of less than 0.8 μg/dL, the midpoint of the first quartile. Also, background blood lead concentrations below this value were adjusted to 0.8 μg/dL in the calculation. Additional details concerning the calculation of eGFR risk in the Monte Carlo assessment are provided in Appendix P.

6.6. Concentration-Response Characterization for Cardiovascular Disease Mortality

Several studies examined the association between cardiovascular disease mortality (CVDM) and lead exposure (Lustberg and Silbergeld, 2002; Schober et al., 2006; Cocco et al., 2007; Khalil et al., 2009; Lin et al., 2011; Menke et al., 2006; Neuberger et al., 2009; Moller and Kristensen 1992; Weisskopf et al., 2009). All but two of these studies reported an association between blood lead and CVDM (Moller and Kristensen 1992; Weisskopf et al., 2009). Weisskopf et al. (2009), however did report an association between bone lead and increased mortality.

Menke et al. (2006) was chosen as the strongest study for this analysis, as described in Exhibit B of *Developing a Concentration-Response Function for Pb Exposure and Cardiovascular Disease-Related Mortality* (US EPA 2014b), also being peer reviewed with this Approach document and its appendices. See this report for a detailed discussion of the CVDM concentration-response function and discussion of related issues. The EPA (2014b) report, and relevant details supporting the use of the study and the application of the equations, are briefly summarized here.

The Menke et al. (2006) study was selected because it used a nationally representative NHANES III sample of men and women whose blood lead concentrations were lower than many previous studies (mean = 2.58 µg/dL), controlled for a wider range of potential confounders, tested for interactions with lead with other covariates, considered concentration-response relationships, and examined mortality from specific cardiovascular diseases (CVDM) and other causes. The Menke et al. (2006) analysis thus addresses some of the weaknesses noted in previous studies. Furthermore, the Menke et al. (2006) findings were supported by a community-based cohort study of women ages 65–87 years, in which higher effect estimates were observed for mortality from cardiovascular disease than for all-cause mortality (Khalil et al., 2009).

Menke et al. (2006) examined all-cause and cause-specific mortality using NHANES III data, in participants at least 18 years of age. They were followed for up to 12 years after their blood lead was measured, and 1,661 deaths were identified from the National Death Index. The cause of death was determined using either International Classification of Diseases (ICD) revision 9 or 10 (WHO 1990). The mean blood lead level of participants at baseline was 2.58 µg/dL, the 80th percentile was 4.9 µg/dL, and the maximum was 10 µg/dL. Participants were categorized into blood lead tertiles based on the weighted population distribution. Blood lead ranges for the tertiles were <1.93 µg/dL, 1.94–3.62 µg/dL, and ≥3.63 µg/dL. To analyze the association between blood lead and mortality, follow-up for each participant was calculated as the time between their NHANES III examination and the date of death, the date on which they turned 90 years of age, or December 31, 2000, whichever occurred first. The hazard ratios and 95 percent confidence intervals were calculated by multivariable Cox regression models for all-cause cardiovascular, myocardial infarction, stroke, and cancer mortality by comparing each tertile with the first (low-lead) tertile (Table 6-5). A hazard ratio (HR) is similar to an odds ratio. Both are measures of a relative change in the risk of an event (such as heart disease incidence or eGFR > 60). Both can control for the effect of other covariate characteristics. A HR is also specifically weighted based on the time when events occurred.

Table 6-5. Hazard Ratios and 95% Confidence Intervals of All-Cause, Cardiovascular Disease, Myocardial Infarction, and Stroke Mortality Associated with Tertile of Lead

	Tertile 1 (<0.09 µmol/L or <1.93 µg/dL)	Tertile 2 (0.09-0.17 µmol/L or 1.94-3.62 µg/dL)	Tertile 3 (≥0.18 µmol/L or ≥3.63 µg/dL)	p_{trend}
All-cause mortality, n	252	470	939	
Age, race-ethnicity, and sex adjusted	1.00	0.97 (0.76–1.23)	1.37 (1.15–1.64)	<0.001
Multivariable 1 adjusted[a]	1.00	0.93 (0.73–1.19)	1.30 (1.08–1.56)	<0.001
Multivariable 2 adjusted[b]	1.00	0.91 (0.72–1.15)	1.25 (1.04–1.51)	0.002
Cardiovascular disease mortality, n	104	219	443	
Age, race-ethnicity, and sex adjusted	1.00	1.01 (0.68–1.51)	1.51 (1.07–2.14)	0.004
Multivariable 1 adjusted[a]	1.00	1.06 (0.70–1.60)	1.64 (1.14–2.35)	0.001
Multivariable 2 adjusted [b]	1.00	1.03 (0.69–1.55)	1.55 (1.08–2.24)	0.003
Myocardial infarction mortality, n	50	83	234	
Age, race-ethnicity, and sex adjusted	1.00	0.99 (0.55–1.79)	1.70 (0.99–2.90)	0.011
Multivariable 1 adjusted [a]	1.00	1.05 (0.56–1.97)	2.01 (1.12–3.61)	0.003
Multivariable 2 adjusted [b]	1.00	1.02 (0.55–1.89)	1.89 (1.04–3.43)	0.007

[a] Adjustment included age, race-ethnicity, sex, diabetes mellitus, body mass index (BMI), current or former smoking, alcohol consumption, physical activity, low income, c-reactive protein (CRP), total cholesterol, high school education, urban residence, and post-menopausal status.
[b] Adjustment includes variables in model 1, hypertension, and level of kidney function.
Sample sizes (n) refer to the number of events.
Source: Menke et al. (2006, Table 2).

Menke et al. (2006) performed three analyses to adjust for various potential confounders, and CVDM was significantly associated with blood lead levels in all three models. Tests for a linear trend across tertiles of blood lead were computed by including tertile of lead as a continuous variable in the Cox regression models. This analysis found statistically significant increases in mortality risk as blood lead levels increased for all causes of mortality analyzed except for cancer. The results of this analysis are also presented in Table 6-5 and support the finding of a concentration-response relationship between blood lead and CVDM.

Menke et al. (2006) also conducted a series of regression analyses in which the log of blood lead was included as a continuous variable. Analyses were conducted for the entire cohort and for subgroups of the study subjects, controlling for same variables as in the tertile models. Changes in CVDM associated with an increase in blood lead from 1.46 to 4.92 µg/dL (20th to 80th percentiles) were calculated for each group. The estimated relative risk of CVDM associated with this change in blood lead was 1.53 (95 percent confidence interval was 1.21–1.94). The results of these models (with log [blood lead] included as a continuous variable) were used as the basis for the CVDM concentration-response function, as discussed in the following section.

The hazard ratio estimates shown in Table 6-6 were derived from covariate-adjusted Cox regressions, and the dependence of mortality on blood lead in these regressions is expressed in the regression coefficients, (βs) estimated in the regressions. These β values can therefore be used to estimate the changes in CVDM for changes in CVDM associated with the increased blood lead levels due to renovation. The original Menke et al. (2006) article did not include β estimates, but the study authors provided the values to EPA for the report, *Developing a Concentration-Response Function for Pb Exposure and Cardiovascular Disease-Related Mortality,* and they also were used here.

EPA's approach for estimating CVDM due to increased blood lead used the β estimates derived separately for men and women by Menke et al. (2006). Use of the gender-specific values (rather than βs for more narrowly defined subpopulations) was intended to provide estimates that are most representative of the U.S. adult population as a whole. The β values and standard errors for men and women from the Menke et al. (2006) analysis were 0.25 (0.20) and 0.40 (0.11), respectively.

The Monte Carlo concentration-response algorithm used to estimate individual CVDM risks was very similar to that for changes in kidney function, as described in Section 6.5.1.

Table 6-6. Summary of Adjusted Hazard Ratios for a 3.4-Fold Change in Blood Lead

Subgroup	Hazard Ratio of All–cause Mortality (95% CI)	Hazard Ratio of Cardiovascular Disease–related Mortality (95% CI)
Age (years)		
<60	1.75 (1.25–2.44)	2.00 (1.24–3.22)
≥60	1.31 (1.08–1.58)	1.49 (1.12–1.99)
Race-Ethnicity		
Non-Hispanic white	1.32 (1.09–1.60)	1.49 (1.12–1.99)
Non-Hispanic black	1.23 (0.99–1.52)	1.13 (0.79–1.61)
Mexican-American	1.17 (0.86–1.60)	1.55 (0.90–2.68)
Sex and Menopausal Status		
Male	1.41 (1.11–1.78)	1.35 (0.84–2.18)
Female	1.24 (1.00–1.54)	1.63 (1.25–2.11)
Pre–menopausal	1.02 (0.54–1.95)	2.71 (0.93–7.91)
Post–menopausal	1.24 (1.00–1.54)	1.46 (1.04–2.03)
Residence		
Rural	1.28 (1.05–1.54)	1.41 (1.01–1.96)
Urban	1.42 (1.18–1.72)	1.75 (1.19–2.56)
Smoking		
Never	1.21 (0.93–1.58)	1.57 (1.10–2.24)
Former	1.61 (1.33–1.94)	2.07 (1.49–2.89)
Current	1.34 (0.96–1.87)	1.05 (0.54–2.04)
Body Mass Index (kg/m^2)		
<25	1.51 (1.16–1.96)	2.02 (1.32–3.11)
≥25	1.28 (1.03–1.58)	1.34 (0.94–1.91)
Hypertension		
No	1.31 (1.08–1.58)	1.48 (0.96–2.26)
Yes	1.32 (1.09–1.60)	1.49 (1.15–1.94)
Diabetes		
No	1.37 (1.19–1.58)	1.59 (1.31–1.92)
Yes	1.12 (0.73–1.71)	1.16 (0.67–2.00)
Estimated Glomerular Filtration Rate (mL/min/1.73m^2)		
<60	1.44 (1.01–2.06)	1.75 (1.06–2.88)

Subgroup	Hazard Ratio of All–cause Mortality (95% CI)	Hazard Ratio of Cardiovascular Disease–related Mortality (95% CI)
≥60	1.32 (1.12–1.56)	1.49 (1.18–1.89)
Overall	1.34 (1.16–1.54)	1.53 (1.21–1.94)

In the Monte Carlo simulation, blood lead levels were modeled twice for each hypothetical individual, once with only background exposures, and again after renovation. Each individual was modeled as male or female and blood lead measurements were assumed to occur at randomly chosen ages greater than or equal to 18 years. EPA chose to estimate changes in CVDM as a function of both concurrent and lifetime average blood lead concentrations. Risks were estimated based on the change in blood lead, much like changes in kidney function, as:

$$CVDM_{a,g} = CVDM_{0,a,g} * e^{(\beta+\varepsilon)*\Delta lnPbB}$$

$$\Delta lnPbB = \ln((PbB_{Renovation}) / (PbB_{Background}))$$

Where:

$CVDM_{a,g}$ = the estimated age- and gender-specific risk after renovation

$CVDM_{0,a,g}$ = the age- and gender-specific background (general population) CVDM risk obtained from the CDC, as discussed further in Appendix P

β = the regression coefficient

ε = a random sample drawn from a normal distribution with mean zero and a standard deviation equal to the estimated standard error of the coefficient.

Including ε in the equation incorporated the statistical uncertainty in the regression coefficient into the estimation process, but, as noted previously, did not capture all sources of individual variability in the analysis.

The output of the analysis was an estimate of individual CVDM risk for an individual whose blood lead level was affected by renovation. The sum of the individual risks across the simulation can be interpreted as the total estimated CVDM in the population. The approach described above is essentially the same as that described in US EPA (2014b), except that it estimates changes in risks for hypothetical individuals and aggregates the results, rather than calculating risks for segments of the population. This method allowed for the incorporation of heterogeneity of individual exposure scenarios into the population risk estimate and allowed for differences in individual response to exposure (characterized by the variability in the regression coefficients) to be included in the analysis. The quantity

$CVDM_{a,g}/CVDM_{0,a,g}$ represents the calculated hazard ratio for an exposed individual and CVDMa,g − $CVDM_0$,a,g is the extra risk.

Another source of uncertainty in the estimates is potential differences in the survival rates and disease patterns in the U.S. general population compared to the pattern observed among the Menke et al. (2006) subjects. The Menke et al. study estimated mortality risks occurring for a maximum follow-up duration of 12 years. Whether this same pattern of risk (that is, the estimated hazard ratios) would remain the same for the entire lifespan of the exposed population is unknown.

Because the detection limit for blood lead measurements in the Menke et al. (2006) study was 1.0 μg/dL, CVDM risks were not estimated for blood lead concentrations below this level. A hazard ratio of 1.0 was assigned to individuals whose post-renovation blood lead was less than 1 μg/dL, and any background estimates below this value were adjusted to 1 μg/dL for the purposes of calculating Δln(blood lead). Also, because of larger uncertainty associated with estimating CVDM at high blood lead concentrations, risks were limited to post-renovation blood lead values up to 5.98 μg/dL (the 90th percentile in the Menke et al. cohort). Post-renovation blood lead estimates greater than this value were adjusted downward to 5.98 μg/dL when calculating Δln(blood lead).

6.7. Summary of Health Effect Concentration-Response Functions Used in the Approach

Based on the discussion in Sections 6.1 to 6.6, the four health effects were represented using the equations and parameters shown in Table 6-7. Each equation depends on a comparison between the post-renovation blood lead and the background blood lead, although the form of the comparison varies. For IQ, CVDM, and kidney effects, the comparison term is:

$$\Delta lnPbB = \ln\left(\frac{PbB_{Renovation}}{PbB_{Background}}\right)$$

while for low birth weight the comparison term is:

$$\Delta\sqrt{PbB} = \sqrt{PbB_{Renovation}} - \sqrt{PbB_{Background}}$$

The difference in mathematical form of the comparison term is related to the form of the regression equation that was used to fit the data in each of the health effect studies. For the Approach, the "$PbB_{Renovation}$" is the total (background plus renovation-related) blood lead following the renovation. The "$PbB_{Background}$" is the background blood lead at the given age of the individual. Then, using the equations in Table 6-7, the predicted metric is the renovation-related change in the health effect. For IQ and LBW, the change is measured as change in FSIQ (in IQ points) and change in birth weight (in grams). For CVDM and kidney effects, the change is represented using the hazard ratio.

Table 6-7. Summary of Concentration-Response Functions for Approach Health Effects

<table>
<tr><th>Health Effect and Reference</th><th>Equation</th><th>Parameters</th><th>Blood Lead Range and Age Range</th></tr>
<tr>
<td>IQ
Lanphear et al., 2005, with parameter adjustments from Crump et al., 2013</td>
<td>$\Delta IQ = \Delta \ln PbB + \beta * N(0, std.err.)$
$\Delta lnPbB = \ln(\frac{PbB_{Renovation}}{PbB_{Background}})$</td>
<td>β= -2.7
std. err. = 0.5</td>
<td>Post-Reno PbB > 1 µg/dL; If background or post-renovation blood lead is less than 1 µg/dL, round each up to 1 µg/dL.
Age 0 to 10</td>
</tr>
<tr>
<td>LBW
Zhu et al., 2010</td>
<td>$\Delta BW = \Delta\sqrt{PbB} \times \Delta BW_{0,1} + N\left(0, \Delta\sqrt{PbB} \times std.dev.\right)$
$\Delta\sqrt{PbB} = \sqrt{PbB_{Renovation}} - \sqrt{PbB_{Background}}$
$\Delta BW_{0,1}$= *Change in body weight associated with maternal PbB increase from 0 to 1 µg/dL*</td>
<td>$\Delta BW_{0,1}$=2.74 g
std. dev = 2.58 (derived from confidence limits)</td>
<td>Post-Reno PbB > 1 µg/dL; If background or post-renovation blood lead is less than 1 µg/dL, round each up to 1 µg/dL. If Post-Reno PbB>10 µg/dL, use the value at 10 (-86.7 g)
Age 18-49</td>
</tr>
<tr>
<td>Kidney Function
Navas-Acien et al., 2009</td>
<td>$LGFR = LGFR_0 \times e^{(\beta+N(0,std.err.))*\Delta lnPbB}$
$\Delta lnPbB = \ln(\frac{PbB_{Renovation}}{PbB_{Background}})$
$LGFR_o$= *national background prevalence of reduced GFR for an individual of a given age and gender*
$Risk\ Ratio = \frac{LGFR}{LGFR_o}$</td>
<td>β=0.157 (males); 0.467 (females)
std. err. = 0.083
<table>
<tr><th>Age (yrs)</th><th>Female $LGFR_o$</th><th>Male $LGFR_o$</th></tr>
<tr><td>20-29</td><td>0.29</td><td>0.24</td></tr>
<tr><td>30-39</td><td>0.68</td><td>0.58</td></tr>
<tr><td>40-49</td><td>1.97</td><td>1.67</td></tr>
<tr><td>50-59</td><td>5.07</td><td>3.98</td></tr>
<tr><td>60-69</td><td>13.05</td><td>9.27</td></tr>
<tr><td>70+</td><td>25.60</td><td>21.06</td></tr>
</table>
</td>
<td>Post-Reno PbB > 1 µg/dL; If background or post-renovation blood lead is less than 1 µg/dL, round each up to 1 µg/dL.
Age 18-49 and 50-80</td>
</tr>
<tr>
<td>CVDM
Menke et al., 2006</td>
<td>$CVDM = CVDM_0 \times e^{(\beta+N(0,std.err.))*\Delta lnPbB}$
$\Delta lnPbB = \ln(\frac{PbB_{Renovation}}{PbB_{Background}})$
$CVDM_o$= *national background prevalence of CVDM for an individual of a given age and gender*
$HazardRatio = \frac{CVDM}{CVDM_o}$</td>
<td>β=0.25 (males); 0.40 (females)
std. err. = 0.20 (males); 0.11 (females)
<table>
<tr><th>Age (yr)</th><th>Female $CVDM_o$</th><th>Male $CVDM_o$</th></tr>
<tr><td>20-29</td><td>3.70E-05</td><td>7.20E-05</td></tr>
<tr><td>30-39</td><td>1.20E-04</td><td>2.40E-04</td></tr>
<tr><td>40-49</td><td>3.90E-04</td><td>8.30E-04</td></tr>
<tr><td>50-59</td><td>9.40E-04</td><td>2.20E-03</td></tr>
<tr><td>60-69</td><td>2.30E-03</td><td>4.60E-03</td></tr>
<tr><td>70-80</td><td>7.60E-03</td><td>1.20E-02</td></tr>
</table>
</td>
<td>Post-Reno PbB > 1 µg/dL; If background or post-renovation blood lead is less than 1 µg/dL, round each up to 1 µg/dL.
Age 18-49 and 50-80</td>
</tr>
</table>

The different equations will predict different renovation-related health effect changes for different background and renovation-related blood leads. For example, if the background blood lead is 1 μg/dL and the renovation-related blood lead is 9 μg/dL, then the estimated mean IQ change would be

$$\Delta lnPbB = \ln\left(\frac{9+1}{1}\right) = \ln(10) = 2.3$$

$$\Delta IQ = \Delta \ln PbB + \ \beta = 2.3 - 2.7 = -0.4 \, points$$

When the equations are applied in the Approach, the “renovation” blood lead is selected at a certain time post-renovation. Different time periods are selected to capture a range of different post-renovation blood leads, as discussed in Section 7.3.1. With the exception of IQ, the original health studies capture blood lead values used that are point estimates of blood lead taken from typical adults; thus, the blood lead values represent current blood lead levels and do not capture the past exposure history of the individual. In many cases, the adults may have had much larger blood lead values in the past when population-level blood leads tended to be higher than today. In the case of the Approach, the renovation is a relatively short (months to years) spike in blood lead followed by a return to background levels. Thus, applying these health effect equations to a post-renovation short-lived blood lead spike as opposed to a chronic lead exposure introduces uncertainty in the Approach, as discussed in Section 9.2.3.

Table 6-8 provides examples of the results of the equations assuming a background blood lead of 1 μg/dL and the renovation-related blood lead shown in each row. In the Monte Carlo simulations, the background values and the renovation-related values will both vary for each iteration, so this table represents an example at a particular background blood lead. Figure 6-1 depicts these predicted health effect changes in graphical form, where the upper and lower 95th percent confidence intervals are also shown.

Table 6-8. Post-Renovation Blood Lead Values and Associated Health Effect Magnitudes in Approach

Renovation-Related Blood Lead Change (µg/dL) *	IQ (IQ points)			BWR (g)		
	IQ	Lower 95th Perc.	Upper 95th Perc.	BWR	Lower 95th Perc.	Upper 95th Perc.
0 (1)	0.0	1.0	−1.0	−27.4	−17.1	−37.8
1 (2)	−1.8	−0.8	−2.9	−38.8	−24.1	−53.4
2 (3)	−2.9	−1.9	−4.0	−47.5	−29.6	−65.4
3 (4)	−3.7	−2.6	−4.7	−54.8	−34.2	−75.5
4 (5)	−4.3	−3.2	−5.3	−61.3	−38.2	−84.4
5 (6)	−4.7	−3.7	−5.8	−67.2	−41.8	−92.5
6 (7)	−5.2	−4.1	−6.2	−72.5	−45.2	−99.9
7 (8)	−5.5	−4.5	−6.6	−77.6	−48.3	−106.8
8 (9)	−5.8	−4.8	−6.9	−82.3	−51.2	−113.3
9 (10)	−6.1	−5.1	−7.1	−86.7	−54.0	−119.4

Renovation-Related Blood Lead Change (µg/dL) *	CVDM Hazard Ratio			Kidney Effects Risk Ratio		
	CVDM	Lower 95th Perc.	Upper 95th Perc.	GFR	Lower 95th Perc.	Upper 95th Perc.
0 (1)	1.00	0.61	1.39	1.00	0.84	1.16
1 (2)	1.19	0.80	1.58	1.11	0.95	1.28
2 (3)	1.32	0.92	1.71	1.19	1.03	1.35
3 (4)	1.41	1.02	1.81	1.24	1.08	1.41
4 (5)	1.50	1.10	1.89	1.29	1.12	1.45
5 (6)	1.57	1.17	1.96	1.32	1.16	1.49
6 (7)	1.63	1.23	2.02	1.36	1.19	1.52
7 (8)	1.68	1.29	2.07	1.39	1.22	1.55
8 (9)	1.73	1.34	2.12	1.41	1.25	1.57
9 (10)	1.78	1.39	2.17	1.44	1.27	1.60

* All equations use a renovation-related blood lead as shown. The background blood lead is assumed to be 1 µg/dL, close to current adult background levels. The total post-renovation blood lead is shown in parentheses.

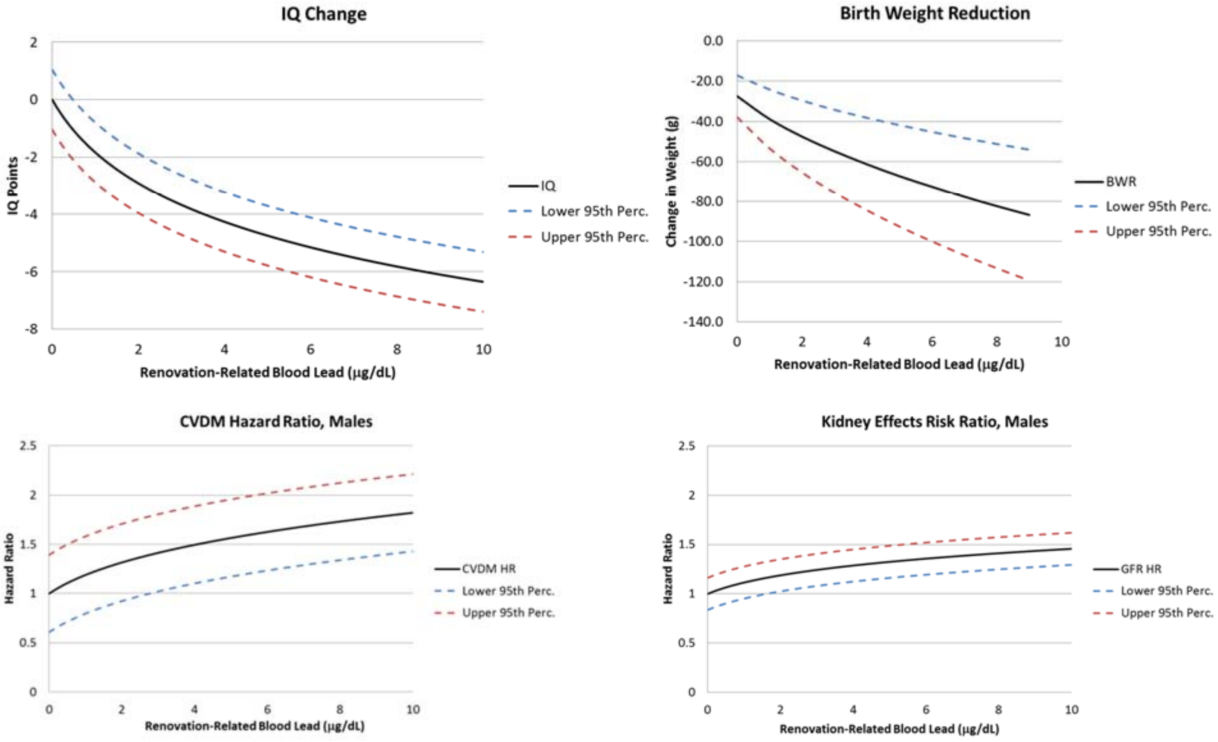


Figure 6-1. Renovation-Related Blood Lead Values and Associated Health Effect Magnitudes

7. Implementing the Monte Carlo Approach

Sections 3 through 6 provide the equations used to estimate the necessary media concentrations and health effects for different renovation conditions. In general, the equations appear with individual variable values (rather than as distributions). As discussed in Section 2.9, a Monte Carlo approach was developed around these equations so that the variability in the necessary input parameters was incorporated. Each variable was defined as either a:

- scenario variable,
- sample variable, or
- fixed variable.

This section describes how the variables were evaluated to choose which should be scenario variables and which are expected to be the key Monte Carlo (sampled) variables. The section also describes how activity patterns and exposure timing characteristics were combined with population-level background lead intakes to develop specific exposure scenarios from the general equations. Finally, the section describes how the Monte Carlo model was tested prior to implementation of all the scenarios.

7.1. Developing Exposure Scenarios

As discussed above and in Section 2.9, scenario variables are key variables that vary discretely so that they can be evaluated in their various combinations after Monte Carlo modeling. For example, in evaluating results, EPA requires information about the predicted health effects for separate types of renovation activities, so the renovation activity is a scenario variable. Each combination of scenario variables defines one scenario. For example, this might include "largest building size, earliest vintage, trim replacement renovation activity, school building type, with the receptor building 50 ft away." Treatment of discrete scenario variables enables EPA to distinguish between this above scenario and the same scenario with the receptor building 800 ft away.

Sampled variables also vary but do not require explicit discrete treatment and cannot be evaluated discretely after Monte Carlo modeling. For example, each receptor building type will have a different building volume; the Approach varies the volume of the buildings according to a nationally representative distribution but does not provide separate answers for each possible building volume, for example, of an industrial building. Thus, building volume is a sampled variable.

To determine which variables would be scenario versus sampled variables, EPA balanced competing priorities of flexibility to evaluate results for different values of a particular variable versus the overall computational demands of the analysis. Each scenario variable added requires additional Monte Carlo scenarios, each requiring thousands of iterations. To determine the number of scenarios and the number of iterations, EPA struck a balance between adequate resolution of the effects of each variable in the results and reasonable computing time.

Test cases were run to evaluate the accuracy of different numbers of iterations and to verify the calculations being performed. Test cases were examined for quality assurance and to ensure the trends were in the appropriate directions based on the trends in the input variables. The Monte Carlo modeling code used a random number seed to ensure reproducibility of the model results.

Developing exposure scenarios also depends on the activity patterns of the simulated individuals, including the time they spend in and outside the building and whether they are exposed to interior, exterior, or both types of renovations. These considerations are discussed below in Section 7.3.

7.1.1. Exteriors

For the exterior analysis, the required scenario variables focused on key characteristics of the renovated building (size and vintage), the renovation activity (activity performed and control options used), the receptor building (building type and distance), and the age group of the person in the receptor building. The sampled (Monte Carlo) variables focused on other variables describing the receptor building and exposed individuals, including the background media concentrations, cleaning habits, amount of time each person in a certain age group spends in the receptor building, etc.

The variables selected as scenario variables for the exterior analysis are shown in Table 7-1**Error! Reference source not found.** These variables were selected because they represent discrete characteristics of the renovated building or receptor building that can be evaluated for a potential rule. When multiplying the different combinations of variables (and accounting for the fact that horizontal containment affects only the closest receptor), these combinations lead to a total of 28,152 scenarios. These scenarios can be evaluated discretely and separately in the future.

Table 7-1. Scenario-specific inputs.

Input	Available Inputs	Units
Renovation Activity	Dry scraping, Wet scraping, Power sanding without HEPA, Power sanding with HEPA, Heat gun, Needle gun without HEPA, Needle gun with HEPA, Window/door replacement, Trim replacement, Torching, Demolition	n/a
Distance from Renovation	5, 50, 150, 300, 650, and 800	ft
Size of Renovated Building	F1T1, F1T2, F1T3, F2T1, F2T2, F2T3, F3T1, F3T2, F3T3	n/a
Type of Receptor Building	Agricultural, Industrial, Commercial, Education, Residential	n/a
Vintage of Renovation	Pre-1930, 1930-1949, 1950-1959, 1960-1979	n/a
Horizontal Containment	Present or not present	n/a
Vertical Containment	Present or not present	n/a
Age Groups	0–10, 18–49, 50–80	n/a

The Monte Carlo (sampled) variables for the exterior analysis are shown in

Table 7-2. All other variables are kept fixed in the analysis. These sampled variables were varied using distributions because

- They were expected to vary significantly,
- They play a relatively significant role on the predicted media concentrations and health effects, and
- Data sources could be identified to inform the choice of the distribution.

Of these variables, the receptor building volume, the air exchange rate, and the cleaning frequency influenced the renovation-related media concentrations because all three affect the residence time of the lead-containing dust in the receptor building. In addition, the time spent in the building will affect the overall exposure to the renovation-derived lead dust. These variables are examined further in the sensitivity analysis in Section 8.

Table 7-2. Sampled Variables for Exterior Analysis

Parameter	Units	Distribution Type
Wall Loading (XRF)	g/cm^2	Lognormal
Receptor Building Vintage	None	Discrete
Receptor Building Height	None	Discrete
Receptor Building Volume	m^3	Lognormal
Receptor Building Air Exchange Rate	hr^{-1}	Normal
Track-in Rate	g/day	Lognormal
Fraction of Dust on Mat	None	Discrete
Track-in from Soil or Hard Surface	None	Discrete
Percent Carpet	None	Discrete
Cleaning Frequency	None	Discrete
Meteorological Region	None	Discrete
Time Spent	None	Discrete
Age within Age Range	None	Discrete
Background Air Concentration	$\mu g/m^3$	Lognormal
Background Soil Concentration	µg/g	Lognormal
Background Dust Loading	$\mu g/ft^2$	Lognormal
Loading to Concentration Conversion Parameters	None	Equation with error T-distribution

7.1.2. Interiors

For the interior analysis, the selection of scenario variables was driven by key characteristics of the renovated building (use type, vintage, room size, and carpeting status) and the renovation activity (activity performed, how much of the room was affected, control options used, number of rooms renovated, and location of the exposed individual in the building). Unlike the exterior analysis, however, these combinations of variable values could not be constrained to a reasonable number of scenarios. For example, assuming 5 use types, 5 vintages, 3 rooms sizes, 2 carpeting options, 100 combinations of paint removal and other renovation activities, 12 options for how much of the rooms was affected (both layers removed and fraction of room renovated), 4 control options, 3 age groups, and all the various receptor locations results in more than 9 million unique scenarios, each of which would require between 1,000 and 10,000 iterations. This large number of scenarios is not computationally feasible but accounting for this range of potential scenarios is required to cover the potential range of dust loadings in the different buildings.

For this reason, the interior analysis did not model all the scenarios directly; instead, it employed a "lookup table approach." The fundamental idea in this approach is that the exposure calculations can be separated into two separate time periods:

1. Estimation of the dust loadings during the renovation (dust generation and rest-of-renovation) in the room where the person is located, and
2. Estimation of the dust loadings after the renovation (routine cleaning phase), along with the resulting blood lead and health effect results.

The scenario variables were then broken into two accompanying categories:

1. Variables that affect only the during-renovation dust loadings, and
2. Variables that affect the post-renovation dust loadings.

These two different categories are shown in Finally, the rest-of-renovation durations were examined for each of the dust-generating duration bins. Again, the 5th, 25th, 50th, 75th, 90th, 95th, 99th, and 100th percentiles were calculated and then aggregated when adjacent ones were within 24 hours (3 working days) of each other.

This analysis gave a series of nested bins that specified a unique combination of dust-generating phase and rest-of-renovation loadings and durations. The analysis was repeated for each building type and carpet status. The result was a total of 301,930 scenarios to be run in the Monte Carlo model.

Table 7-3. In the lookup table approach, all the different loadings and renovation durations associated with the different scenarios (the "Intermediates" column in Finally, the rest-of-renovation durations were examined for each of the dust-generating duration bins. Again, the 5th, 25th, 50th, 75th, 90th, 95th, 99th, and 100th percentiles were calculated and then aggregated when adjacent ones were within 24 hours (3 working days) of each other.

This analysis gave a series of nested bins that specified a unique combination of dust-generating phase and rest-of-renovation loadings and durations. The analysis was repeated for each building type and carpet status. The result was a total of 301,930 scenarios to be run in the Monte Carlo model.

Table 7-3) were calculated for every scenario. This resulted in millions of unique combinations of:

1. Dust-generating phase dust loading in the room of occupancy,
2. Rest-of-renovation phase dust loading in the room of occupancy,
3. Duration of the dust-generating phase, and
4. Duration of the rest-of-renovation phase.

Then, this complete list was used to select a representative number of combinations that cover the range of dust loadings and durations. The representative dust generation phase dust loadings, rest-of-renovation dust loadings, dust-generation phase durations, and rest-of-renovation duration values and combinations were used to populate a "lookup table." The values across these four variables resulted in 301,930 unique combinations. These unique combinations were run through the Monte Carlo model (along with the sampled variables) to estimate health effects for each dust loading/duration combination. As a final step, as shown in Figure 7-1, the original scenario table was used to locate the closest matching loadings and durations in the lookup table, and the results were linearly interpolated to estimate the scenario results. This approach has the advantage of enabling millions of scenarios to be estimated, using a smaller subset of representative scenarios.

To arrive at the appropriate number of scenarios to run that would capture the millions of scenarios without introducing large (e.g., >5 percent) errors, the loadings and durations were analyzed using the SAS statistical software package (SAS Institute, 2012). The SAS code started with the dust-generating loading, as follows.

Dust-Generating Loading Bins: The SAS code estimated percentiles 0th, 2nd, 4th, 6th, …., 98th, and 100th. Then, the code looped back through these bins and collapsed bins that were within 5 $\mu g/ft^2$ of each other. This tolerance value was selected because appreciable differences in the renovation-related health effect predictions were not expected to be influenced by this decision to set dust loading bins at 5 μg/ft2 versus 2, 4, or 6 $\mu g/ft^2$.

For each Dust-Generating Loading Bin, create Rest-of-Renovation Loading Bins: Next, the rest-of-renovation loadings were examined for each dust-generating bin. Again, the 0th, 2nd, 4th, 6th, …., 98th, and 100th percentiles were calculated and then aggregated when adjacent ones were within 5 $\mu g/ft^2$ of each other.

For each Rest-of-Renovation Loading Bin, create Dust-Generating Duration Bins: Next, for each dust-generating loading bin, the durations were used to estimate the 5th, 25th, 50th, 75th, 90th, 95th, 99th, and 100th percentiles. The code then looped back through these bins and collapsed any that were within 24 hours (3 working days) of each other. Again, 3 days was selected because appreciable differences in the renovation-related health effect predictions were not expected to be influenced by this decision to set durations of exposure at 3 days versus 1, 2, or 4 days.

For each Dust-Generating Duration Bin, create Rest-of Renovation Duration Bins: Finally, the rest-of-renovation durations were examined for each of the dust-generating duration bins. Again, the 5th, 25th, 50th, 75th, 90th, 95th, 99th, and 100th percentiles were calculated and then aggregated when adjacent ones were within 24 hours (3 working days) of each other.

This analysis gave a series of nested bins that specified a unique combination of dust-generating phase and rest-of-renovation loadings and durations. The analysis was repeated for each building type and carpet status. The result was a total of 301,930 scenarios to be run in the Monte Carlo model.

Table 7-3. Separation of Scenario Variables Into Categories for Lookup Table Approach

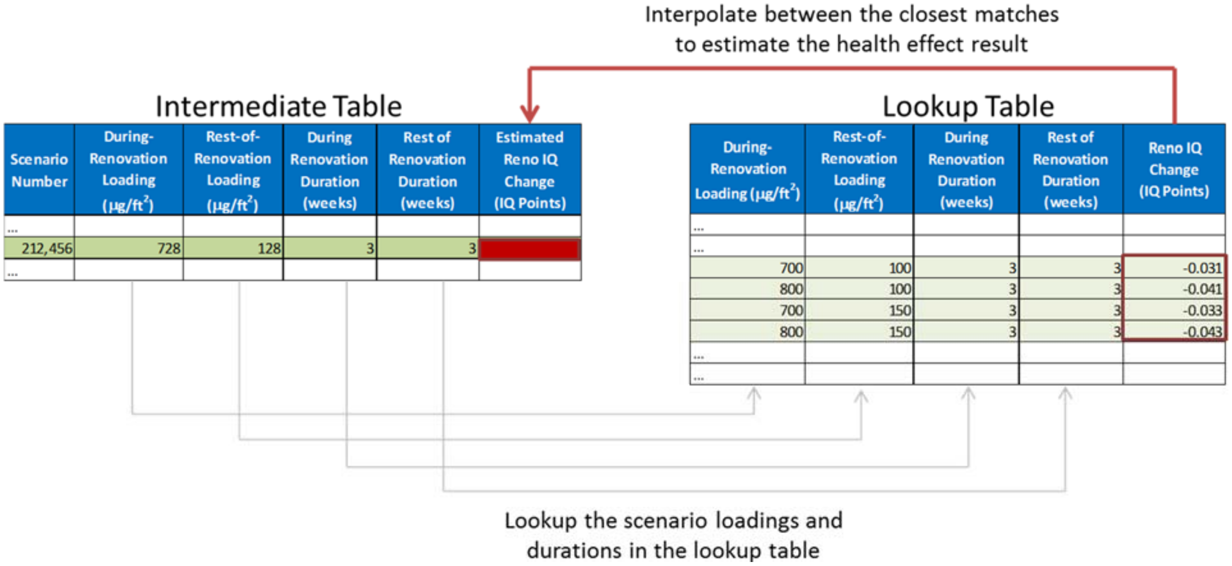
1. Variables That Only Affect Renovation Exposure	Intermediates: Renovation Loadings and Durations	2. Variables that Affect Post-Renovation Exposure
Scenario Table	**Intermediate Table**	**Lookup Table**
■ Renovation activities and intensities ■ Building configurations/room sizes ■ Rooms renovated ■ Control option ■ Location of exposed individual ■ Work area sizes ■ Vintage	■ Loadings during dust generating phase ■ Loadings during rest of renovation phase ■ Duration of dust generating phase ■ Duration of rest of renovation phase	■ Age group ■ Carpet/Not Carpet, to determine the cleaning efficiency ■ Building type, to determine the time spent distribution ■ Exterior renovation soil concentration and matching air concentration
These variables are used to estimate intermediates ➡	These variables become inputs to the Monte Carlo model ➡	Monte Carlo results

The Monte Carlo model samples from the sampled variables to estimate variation across the exposure scenario. For the interior analysis, these variables are shown in

Table 7-4. As with the exterior analysis, these Monte Carlo variables were varied using distributions because

- They were expected to vary significantly,
- They play a relatively significant role on the predicted media concentrations and health effects, and
- Data sources could be identified to inform the choice of the distribution.

Of these variables, those associated with dust removal (cleaning frequency) and with the amount of time spent in the building (time spent) are expected to have a significant effect on the results. These variables are examined further in the sensitivity analysis described in Section 8.



Interpolate between the closest matches to estimate the health effect result

Intermediate Table

Scenario Number	During-Renovation Loading (µg/ft²)	Rest-of-Renovation Loading (µg/ft²)	During Renovation Duration (weeks)	Rest of Renovation Duration (weeks)	Estimated Reno IQ Change (IQ Points)
...					
212,456	728	128	3	3	🟥
...					

Lookup Table

During-Renovation Loading (µg/ft²)	Rest-of-Renovation Loading (µg/ft²)	During Renovation Duration (weeks)	Rest of Renovation Duration (weeks)	Reno IQ Change (IQ Points)
...				
...				
700	100	3	3	-0.031
800	100	3	3	-0.041
700	150	3	3	-0.033
800	150	3	3	-0.043
...				
...				

Lookup the scenario loadings and durations in the lookup table

Figure 7-1. Illustration of the Lookup Table Method to Link Specific Scenarios with the Answers in the Lookup Table

Table 7-4. Sampled Variables for Interior Analysis

Parameters	Units	Distribution Type
Wall Loading (XRF)	g/cm^2	Lognormal
Fraction of Paint Removed	None	Discrete
Building Floor Area	m^3	Lognormal
Track-in Rate	g/day	Lognormal
Fraction of Dust on Mat	None	Discrete
Fraction of Exterior and Interior Renovations Occurring at the Same Time	None	Discrete
Cleaning Frequency	None	Discrete
Time Spent	None	Discrete
Age within Age Range	None	Discrete
Background Air Concentration	$\mu g/m^3$	Lognormal
Background Soil Concentration	µg/g	Lognormal
Background Dust Loading	$\mu g/ft^2$	Lognormal
Loading to Concentration Conversion Parameters	None	Equation with error T-distribution

7.2. Estimating Time-Dependent Background Intakes

Once the various renovation scenarios are defined, the renovation-related exposure estimates must be placed within the context of background lead exposure for an individual. Because the current analysis covered both children and adults up to age 80, background lead intakes (and thus background blood lead) are highly variable over the lifetime of some modeled individuals. In particular, changes in regulations related to lead in gasoline resulted in a dramatic change in intakes and blood lead values for children, adolescents, and adults between 1980 and today. To place the magnitude of the renovation-related blood lead in the context of lifetime exposure, the full intake history from birth for each individual was estimated and captured in the Approach.

To capture this change in intake, the NHANES blood lead data from each available NHANES year were used to estimate the average blood lead for an individual for each year, ages 0 to 80. The available NHANES years included 1976–1980, 1988–1991, 1991–1994, 1999–2000, 2001–2002, 2003–2004, 2005–2006, 2007–2008, 2009–2010, and 2011–2012. Thus, the data gave average blood lead values for a person aged 0, aged 1, aged 2, etc. in each available NHANES dataset. The population was then split into age groups expected to have similar intakes over their lifetimes, including those born 1930–1954, 1955–1966, 1967–1976, 1977–1986, 1987–1996, and Post 1996. These age groups were selected to group individuals according to both overall age and age during rapidly changing intake time periods.

An initial estimate was then provided for a series of different periods for each age range. Intakes were kept constant up until 1984 (for those born before 1984) and then were scaled based on the ratio of the 1984 blood lead to the current blood lead in 1993, 2000, 2005, and 2014. In this way, the intakes could taper slowly from the leaded gasoline era values to the current 2014 estimates. The year 1984 was selected as a time roughly in the middle of the U.S. lead gas phase out (1973–1996). The Leggett model was run assuming the different intake values, and the sum of the mean square error terms between the estimated and actual blood lead values from NHANES for each age group (males and females together) were estimated. The initial intake was then changed and Leggett was rerun until the sum of the mean square errors was at a minimum.

The result was an intake profile for each individual based on birth year. The intakes changed in 1984, 1993, 2000, 2005, and 2014 so that the blood lead predicted in each year best matched the NHANES blood lead values for individuals at that age in that year. Additional details about this analysis are provided in Appendix N.4.

7.3. Building Time Series of Exposure and Blood Lead

The Approach description in Sections 2 through 7 focuses on the media concentrations (air, soil, hard surface, indoor dust) for locations near interior and exterior renovations. To simulate exposure for different individuals, these media concentrations were placed within the context of their overall lifetime lead exposures. In particular, the media concentrations were matched with an age when the renovation occurs, and other age-specific exposure factors and activity patterns used to characterize the hypothetical individual's net lead intake related to the renovation concentrations.

7.3.1. Selection of Ages at Renovation and at Blood Lead Measurement

EPA evaluated health effects for individuals in three age ranges: 0-10, 18-49, and 50-80. However, within each age group, an individual can experience renovation at different ages. Thus, U.S. Census data were used to find probability distributions for the population in each age range. These distributions are shown in Appendix B. Then, for each Monte Carlo iteration, the age group distribution was sampled to determine the age of the person at renovation during that iteration. The intakes were constructed so that a person has background intake (see Section 7.2) up until the age at renovation and has background intake and renovation-related intake after the renovation. The blood lead model can then be run to estimate blood lead at any point after the renovation.

The health effects used in the Approach, with the exception of IQ, are based on effects from cross-sectional epidemiology studies. As such, blood lead and health effect statistics are available at a single age for an individual without knowledge of the prior history of exposure for that individual. To match this study design, the blood lead post-renovation would have to be saved in the modeling at a specific point to be used in the health effect concentration-response equations. The blood lead value, however, will be highly dependent on the point after renovation selected for analysis. Ideally, the time chosen should be selected using information about the specific health effect and the biological window of susceptibility or necessary duration of elevated blood lead to result in the effect. For lead exposure in all of the known health effects, however, this information about the necessary duration of exposure is not known and is not available in the literature. For low birth weight, the duration of pregnancy might be the relevant biological window, whereas a longer-term duration could be more relevant for chronic health effects like kidney disease and CVDM.

To overcome this data shortfall, EPA captured the concentration-response function health effect predictions for a range of blood lead measurement times, where the "measurement time" is defined as the time post-renovation when the blood lead and health effect are assumed to be evaluated in the modeled individual. To select the maximum measurement time to use, the Approach focuses on evaluating the response to the most recent renovation experienced by the individual. During the person's lifetime, he or she will move through a variety of P&CBs, all of which will be renovated on different frequencies and timescales. To establish the window of time during which the most recent P&CB renovation took place, data were used that detail statistics for different types of renovation jobs in P&CBs. As discussed in more detail in Appendix L, the average frequency of renovation for a given building was between 1.3 years (low) and 4.2 years (high). These values are estimated from the RSMeans Construction manual, and the high and low values account for assumptions about whether different renovation activities happen concurrently or separately. The high value was used as an upper bound for the time since the last renovation experienced by the individual in a P&CB. Thus, blood lead values for the individual were captured at nine intermediate time-since-renovation values, with the maximum value set to 4.2 years, as shown in Table 7-5.

Table 7-5. Blood Lead Measurement Times Relative to the Renovation

Estimated Time Since Last Renovation (Age at Blood Lead Measurement)
1 month
5 months
10 months
15 months
20 months
25 months
30 months
40 months
50 months (or 4.2 years)

Blood lead incremental changes and health effect changes related to the renovation were then calculated for each individual at each of these time-since-renovation values. The Monte Carlo model returns statistics about each for the three age groups. Figure 7-2 shows an example of two iterations, one where the renovation occurs at 0.6 years old and one where it occurs at 4.8 years old. The dashed lines represent the different times the blood lead values are captured and the health effect results are estimated for these iterations.

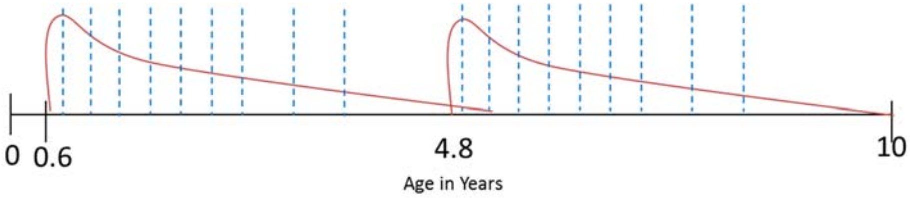


Figure 7-2. Illustration of Blood Lead Measurement Times (dashed lines) for Two Different Age-at-renovation Values (0.6 and 4.8 years old) in the 0- to 10-year-old Age Group

As an additional blood lead metric, the lifetime average blood lead is also estimated for each iteration and age group. This lifetime average is defined as the average from birth until the post-renovation time when blood lead returns to the background value. This metric, rather than being a biologically based metric, is an exposure-based one. Because the health effect studies and other literature do not provide information on a biologically relevant window of susceptibility for the health effects, the exposure-based lifetime average definition is used as a surrogate. This lifetime average is depicted in the lower panel of Figure 7-3.

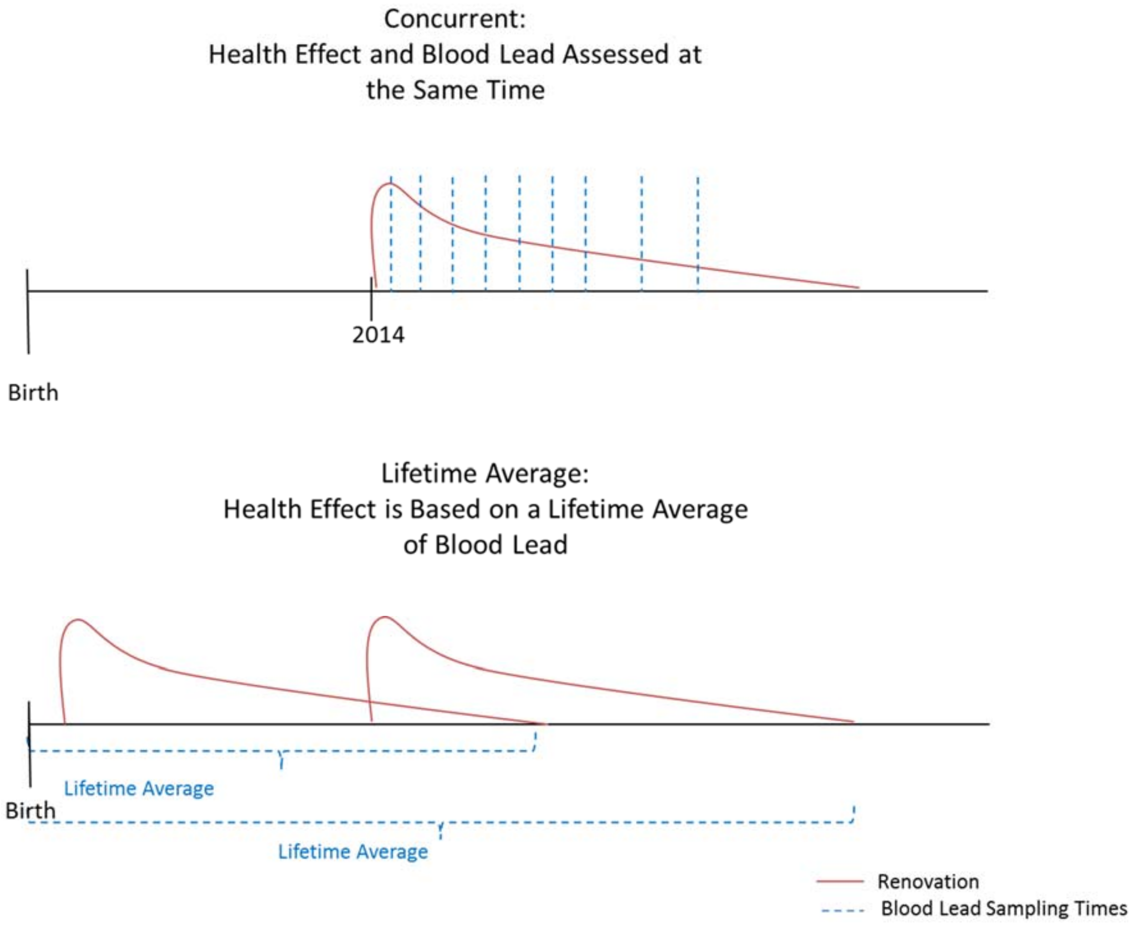


Figure 7-3. Diagram of Concurrent and Lifetime Average Blood Lead Metrics in the Approach

7.3.2. Age-specific Activity Patterns and Exposure Factors

In addition to the age at which the renovation occurred, other age-specific exposure factors are used to estimate exposure to specific renovation-related media concentrations.

Activity Patterns

The Approach incorporates the fraction of time spent in the P&CB. This fraction varies by age group and by building type. To estimate the distributions, the CHAD database (US EPA 2014a) was used to reconstruct fractions of time in various buildings based on the unique activity entries. The building types used in the analysis were mapped to the CHAD building types, and many different percentiles of time spent for four age groups and exterior and interior building types were calculated. Further details of how these calculations were performed are available in Appendix L. These percentiles were then used as a sampled variable in the Monte Carlo code to find the time spent in the renovated building for each age group in each iteration. The effective exposure media concentrations were then estimated as time-weighted averages of background concentrations (when the person is away from the renovated building or receptor building) and background plus renovation-related concentrations (when the person is inside the renovated building or receptor building).

Combining Activity Inside and Outside the Receptor Building or Renovated Building

In addition to being in the renovated building, an individual could also spend time outside the building, experiencing different exposure concentrations. For the exterior analysis, this case is incorporated in the modeling. The exposure factors (discussed below) used in the interior and exterior renovation modeling incorporate both time inside (dust ingestion) and time outside (soil ingestion). For example, a person might exit the building for a period of time (e.g., to eat lunch) and then reenter the building to resume activity. For the interior analysis, soil ingestion was again incorporated into the total particulate intake, with the assumption that the relative soil and dust intake while in and around the renovated building is the same as the relative soil and dust intake for the day as a whole as given in the EPA Exposure Factors Handbook (US EPA 2011). In the case where the exterior of the building is not renovated, the soil lead is expected to remain at background levels, so the person is exposed to background air and soil levels when outside the building.

One final exposure scenario involves a building that is renovated on the exterior and in the interior simultaneously. In that case, a person will be exposed to tracked-in elevated soil lead. Then, they will be exposed to the interior renovation-related lead loading inside the building. The track-in of elevated soil was incorporated into the interior modeling during the routine-cleaning phase.

Exposure Factors

To convert media concentrations to intakes, exposure factors were used. In general, these exposure factors were taken from the age-specific values in the EPA Exposure Factors Handbook (US EPA 2011), and they include the inhalation rate, soil/dust ingestion rate, and fraction of soil/dust ingestion that is from soil. These factors were multiplied by the lead concentrations in the media (air, soil, and dust) to estimate the lead intakes for input in the Leggett blood lead model. The values used are all provided in Appendix N.

7.4. Incorporating Population-Level Biokinetic Differences

The Leggett model was used to estimate the blood lead value for each iteration for the childhood and adult age groups. After combining all iterations within a scenario, the resulting distribution of blood lead estimates represents the variability in the range of hypothetical individuals from the media concentration and lifestyle variable distributions included in the Monte Carlo analysis for that scenario. The distribution of modeling results does not include variability from variables that were set to point estimates in the model. One such set of variables is those that determine the exposure factors (e.g., inhalation and ingestion rates by age) and the biokinetic parameters (e.g., rate of movement of lead from plasma to bone) in the blood lead model. These variables were not incorporated as distributions owing to the overall uncertainty in the parameter estimates themselves and the lack of reliable literature data to use to estimate these distributions.

Thus, to account for these differences, additional variability was incorporated into the iteration-specific blood lead estimate. The Leggett model prediction for the given iteration was treated as the geometric mean of the broader distribution of exposure factors and biokinetic differences. A representative geometric standard deviation (GSD) was then selected and combined with this geometric mean to estimate a series of new iteration-specific blood lead values that accounts for these differences. In particular, for each iteration, the Leggett value (interpreted as the geometric mean) and the GSD were used to estimate 25 blood lead estimates. These 25 values were then used to estimate the blood lead and health effect statistics returned for the scenario as a whole. This decision to use 25 values (as opposed to, for example, 10, 100, or 1000) was made to balance model accuracy with computational performance. Twenty-five was deemed an appropriate number to resolve different parts of the distribution without adding significant runtime and data storage burdens.

For the Approach, a value of 1.9 was selected for this GSD. This value is fairly constant across the NHANES surveys since the year 2000. This value was identified as a reasonable value to use for a diverse population, as discussed in Appendix O.

For bone lead, no similar nationally representative survey spanning both children and adults could be found. Because these data were not available, no GSD was applied to the bone lead estimates from the Leggett model.

7.5. Metrics Saved for Incremental Media Concentrations, Blood Lead and Health Effect Changes

After the blood lead estimates were made and the health effects were all estimated using the concentration-response functions, a series of model statistics was saved to serve as the analytical output of the model.

Table 7-6 shows the full suite of variables that were saved. In each case, the mean, median, standard deviation, maximum, and 5th, 90th, 95th, 99th, 99.5th percentiles were saved to characterize the distribution of model outputs. These metrics allow for comparison across scenarios.

Of the metrics described in Table 7-6, some of these have a counter metric called “fraction of iterations” which shows how often iterations were above a certain values. These allow for comparison within scenarios. Variables which have one or more “fraction of iteration” counters have a *next to them in Table 7-6. Examples of this kind of metric, as distinct from summary statistics across scenarios, are described in Table 8-3 and Table 8-10.

Table 7-6. Model Metrics Saved from the Simulations

Variable	Do Not Depend on Age			Age 0–10			Age 18–49			Age 50–80		
	Total	Bkgnd	Reno Only	Total	Bkgnd	Reno Only	Total	Bkgnd	Reno Only	Total	Bkgnd	Reno Only
Reno Avg Air	✓	✓	✓									
3-month Avg Air*	✓	✓	✓									
Max Soil Conc*	✓	✓	✓									
Max Hard Surface Loading*	✓	✓	✓									
Max Dust Loading*	✓	✓	✓									
Dust Time to Background	✓	✓	✓									
Blood Lead*				✓	✓	✓	✓	✓	✓	✓	✓	✓
Blood Lead Time to Background				✓	✓	✓	✓	✓	✓	✓	✓	✓
Bone Lead						✓			✓			✓
IQ Change*						✓						
Low Birth Weight*							✓	✓	✓			
Kidney Effects, Males, Risk*							✓	✓	✓	✓	✓	✓
Kidney Effects, Males, risk ratio*							✓	✓	✓	✓	✓	✓
Kidney Effects, Females, Risk*							✓	✓	✓	✓	✓	✓
Kidney Effects, Females, risk Ratio*							✓	✓	✓	✓	✓	✓
CVDM, Males, Risk*							✓	✓	✓	✓	✓	✓
CVDM, Males, Hazard Ratio*							✓	✓	✓	✓	✓	✓
CVDM, Females, Risk*							✓	✓	✓	✓	✓	✓
CVDM, Females, Hazard Ratio*							✓	✓	✓	✓	✓	✓

Key:
Shaded box: Not applicable
Checked box: Saved in analysis
Blank box: Does not match the health effect in questions based on the concentration-response function

For each variable, three values were returned: (1) the total (renovation plus background) statistics, (2) the background-only statistics, and (3) the renovation-related statistics. In each case, the total, background, and renovation-related values were estimated for each iteration and the full set of iterations was used to estimate the statistics for each of the three. For the health effects, the renovation-related contribution was determined in different ways for the different mathematical forms of the equations. For IQ, the IQ change itself was interpreted as the renovation-related contribution, so no “total” or “background only” statistics were returned. This treatment reflects the functional form of the concentration-response function, which explicitly estimates IQ change relative to background. For the low birth weight equations, predicted change in birth weight was estimated relative to a blood lead of zero. Thus, the change was estimated for both the “total” blood lead and the “background only” blood lead. The renovation-related portion was estimated as the difference between the two. For cardiovascular disease mortality and kidney effects, the model prediction was interpreted as the “total” contribution, the population-level average responses from CDC were interpreted as the “background only” responses, as the renovation only was the difference between the two. The hazard or risk ratio was also estimated for these health effects, and this ratio represents the ratio of the total to the background-only response.

7.6. Testing the Full Monte Carlo Models

Once the Approach equations and model parameters were defined, the code was implemented and tested. This section describes the tests performed to ensure the model produced accurate and reliable results.

7.6.1. Accuracy

The Approach outlined in this document was implemented using the Python programming language (Version 2.7), including the Numpy, Scipy, Tweepy, and Cython add-ins (Python Software Foundation, 2012). The complete code package developed for this Approach consisted of several modules that performed the lookups, sampling, and calculations; text-based input files specifying the distributions and parameter values; the AERMOD air concentration files; and the Leggett model input tables. The code was written with particular attention paid to the model speed so that all the scenarios and iterations could be run using the minimum required computer resources. The lookup table for the interior Approach was created using code written in the SAS programming language (SAS Foundation, version 9.3, 2012).

All the input parameters were collected in text files. For sampled parameters with defined distributions (normal, lognormal, and uniform), upper and lower bounds were assigned so that the values could not become unrealistically large or small. For normal distributions, the bounds were set at ±2 standard deviations from the mean, while also ensuring that no sampled values were negative. For the lognormal distribution, the bounds were set at ±2 standard deviations for the log-transformed distribution. Standard Python packages were used to sample from the distributions. For variables with discrete values (such as the nine meteorology regions), the cumulative probability distribution of each variable was used to select the appropriate value. For each variable value, the absolute probability of occurrence was assigned based on values in the literature or professional judgment, as described in the Appendices. Then, the cumulative probability distribution is found by taking the sum of the probability of a given value and all previous values. For example, if the probabilities of three different variable values were:

- Probability of A = 0.2
- Probability of B = 0.5
- Probability of C = 0.3

Then, the cumulative probability distribution would be:

- Cumulative Probability of A = 0.2
- Cumulative Probability of B = 0.7
- Cumulative probability of C = 1

The cumulative probability for each value is always between 0 and 1. Thus, a random number between 0 and 1 was selected, and the variable value with a cumulative probability greater than the random number was then used in the Monte Carlo iteration. For example, if the random number were 0.3, then variable value “B” would be selected, while if the random number were 0.8, then the variable value “C” would be selected.

After the code was built, a full code review was performed, and then a series of quality assurance tests was performed to ensure the code was performing correctly. Each lookup and calculation step was designed as a separate function in the code. Python unit tests were used to test each function separately to ensure that the function returned the correct output for a given input. A unit test is a separate test for each function and module in the code to ensure the “unit” provides accurate solutions. In addition, test cases were run in the model, and the trends across different model scenarios were examined to ensure the direction of the trends matched the direction of the trends in the input values. Finally, hand calculations were performed for portions of the code to ensure the code was performing the correct calculations.

7.6.2. Convergence

Next, tests were performed to determine the number of model iterations necessary to ensure proper convergence in both the mean and the 95th percentile statistics in the “worst case” scenario for both the interior and exterior analyses. Full convergence implies that the model returns the same output statistics each time the model is run. During the Monte Carlo sampling, random numbers were used to select the input variable values during each iteration. In the computer code, the progression of random numbers used in the model depends on the seed selected at the outset of the model run. The seed determines the progression of random numbers. Convergence implies that if different seeds are used (so that different random number progressions are used) in two separate model runs, the statistics will not differ beyond a certain pre-specified tolerance. This will indicate the number of iterations is sufficient so that all extreme values in the distributions are being adequately sampled and will return approximately the same statistics each time. For this analysis, a ± 5 percent tolerance value for the mean statistic was set for the convergence testing. This translates to an overall range of 10 percent in the mean statistic.

The exterior model was run with 10,000, 20,000, 30,000 and 50,000 iterations for each of the 15exterior test cases. Each iteration case was run 10 times in the model using different initial seeds (i.e., a different starting random number). Then, the range of means expressed as a percentage of the average across the 10 runs was calculated for each number of iterations. The testing revealed that the 10,000-iteration case achieved a range of 5.6 percent for the mean childhood-renovation-related blood lead statistic and 2.4 percent for the 95th percentile. The 20,000 and 50,000 iteration cases did not offer significant improvement but took much longer to run. Thus, 10,000 iterations was the selected size for the exterior production runs.

For the interior analysis, the model was expected to converge in fewer iterations because fewer variables were sampled. The interior model was run with 1,000, 2,000, 3,000, 4,000, 5,000, 7,500, and 10,000 iterations for each of the 15 interior test cases. The testing revealed that the 3,000-iteration case achieved a range of 6.4 percent for the mean childhood renovation-related blood lead statistic and 7.6 percent for the 95th percentile. This was the smallest number of iterations meeting the ± 5 percent tolerance, so 3,000 iterations was the selected size for the interior production runs.

All scenarios were then run through the model and the resulting blood lead level and health effects statistics were estimated.

8. Results of the Monte Carlo Analysis

8.1. Pre-Screening to determine which Exterior and Interior Scenarios require Monte Carlo

8.1.1. Exteriors

For the Exteriors analysis, each scenario was modeled using worst-case assumptions for sampled variables before deciding whether to include that scenario in the Monte Carlo analysis and run 10,000 iterations. The goal of this approach was to continue testing the model and to determine whether certain scenarios did not require 10,000 Monte Carlo iterations because their worst-case run results indicated health effects very close to background levels (e.g., very low increase in health effects due to renovation activities). Worst-case runs tended to overestimate exposures when compared to maximum or 99th percentile values from Monte Carlo iterations, as indicated during testing runs. Model results were evaluated relative to each other and compared to pre-established criteria for blood lead and health effects.

The first criterion was lifetime blood lead for a 2-year-old child. If a scenario resulted in a lifetime blood lead increase of less than 0.1 μg/dL, it was flagged for possible exclusion from the analysis. Approximately 20 percent of scenarios met this first criterion. While lifetime blood lead can be low for a given scenario, concurrent blood lead directly following renovation (i.e., 1 month) and associated health effects can remain elevated. For this reason, these scenarios were evaluated against health effect levels for each endpoint. These levels were set to be very conservative, using 1-month renovation-related outputs of <0.105 IQ change, <1.003 CVDM hazard ratio, <10 grams in birth weight change, and <1.05 kidney risk ratio. These values were chosen as a point of comparison to limit the number of scenarios and are not intended to reflect any health-based threshold.

The second criterion was whether the scenario resulted in an exceedance of any concurrent health effect level. All scenarios resulted in an exceedance of at least one health effect level, again due to the conservative nature of high exposure estimates and low health effect levels. Some scenarios, however, exceeded only one of the four health-effect thresholds.

For the third criterion was the number of time steps (out of nine total) that resulted in the exceedance of a concurrent health effect level. If a scenario exceeded a health-effect level, using only the one month concurrent values and no other time steps, it was excluded. Finally, health effect criteria were interpreted such that if results were approaching health effect levels, they were considered for inclusion. After consideration of these criteria, 3 percent of the scenarios were identified and did not receive 10,000 Monte Carlo iterations. Maximum dust loadings for eliminated scenarios were also considered and all loadings were very low with the maximum loading of eliminated scenarios being 5 μg/ft^2. These cases were considered when evaluating overall results by categorizing them as "near-background results."

8.1.2. Interiors

For interiors, look-up table values, as described in Section 7.1.2, for the various combinations of dust-generating phase loadings, rest-of-renovation loadings, dust-generation phase durations, and rest-of-renovation durations were evaluated. Testing runs showed that these variables ranged from very low to very high. The very low loading values and the very low durations were evaluated to determine if a level could be established where the combination of lower loadings and short durations would result in very low incremental health effect changes and therefore the scenario could be reasonably excluded. Even the shortest duration and lowest loading combinations, however, when combined with worst-case assumptions for other variables, resulted in incremental health effect changes above screening levels described above for exteriors. Therefore, no loading or duration values were excluded.

8.2. Summary of Results for Exterior Monte Carlo Scenarios

This section summarizes the exterior results from the millions of iterations that were modeled to characterize renovation-related blood lead concentrations and incremental health effect changes for children and adults. The purpose of this section is to provide some insight into the overall magnitude and distribution of results, and the trends in results across different scenario variables.

Throughout this section, blood lead concentrations and IQ changes are presented to one decimal point (i.e., overall resolution of 0.1 μg/dL blood lead and 0.1 IQ point). Hazard and risk ratios are presented to the nearest 0.01 and birth weight is presented to the nearest 0.1 gram. This level of resolution was selected to be consistent with the modeling capabilities. Results are summarized in this section in various ways: a percentile (average, 95th) for a specific incremental environmental media, blood lead concentration, or health effect within a scenario, comparisons of the percent of scenarios across all scenarios that went above a value, and comparison of iterations within a scenario that went above a value.

For all graphs and charts shown throughout Section 8, it is important to reiterate that the results apply only to the exposure scenarios as described for purposes of the Approach. These results do not show the estimated proportion of building types with an estimated media concentration or the estimated proportion of the US population that is predicted to experience the specific blood lead change or incremental health effect. This is because the scenarios have not yet been evaluated to determine how likely or unlikely they are to occur with respect to current work-practices and renovation activities within P&CBs.

8.2.1. Trends across Scenario Variables

Table 8-1 provides a summary of trends observed in the exterior analysis across the scenario variables. Additional graphical representation of these trends is provided in Section 8.3.1.

Table 8-1. Summary of Trends in Exterior Analysis

Trend Category	Trends Observed
Renovation Activity Types	The blood lead changes associated with the renovation tend to decrease with decreasing emission fraction. Needle gun (no HEPA), torching, and power sanding (no HEPA) result in the largest changes. Trim replacement, window/door removal, and heat gun on wood result in the smallest changes. At the closest receptor building, demolition results in the largest blood lead changes; more particle debris and bulk material is created with this activity, which leads to larger track-in and higher indoor dust loadings.
Distance	The blood lead changes decrease quickly with distance from the renovated building. At the closest distance (0 ft, indicating that the renovated building is also the receptor building), 42% of the scenarios estimated mean renovation-related blood lead changes of at least 0.1 μg/dL in children after 5 months. However, at 50 ft that value drops to 15% and at 150 ft it drops to 6%. By 800 ft, only 0.1% of the scenarios exceed a blood lead change of 0.1 μg/dL after 5 months.
Size of Renovated Building Size	The size of the renovated building has a complex effect on the blood lead change. The intermediate size (F1T2, for example) has the lowest blood lead level changes. For buildings with a smaller footprint (F1T1, for example), blood lead changes increase. In this case, the building is narrower with respect to any given receptor building radial; thus, the aerosolized dust is less dilute and is channeled more along one given radial by the wind. For the bigger building (F1T3, for example), the overall increase in lead emitted gives rise to larger blood lead changes in the receptor building occupants. When looking at changes in building size, taller buildings tend to result in lower blood lead changes at the nearest receptor buildings and moderate increases at distant receptor buildings; the wind field is faster at higher stories and carries the lead dust farther from the renovated building.
Age of Renovated Building	The patterns associated with age of the building follow the trends in the amount of lead in the paint for each vintage; thus, pre-1930 buildings have the greatest blood lead changes followed by 1930–1949, then 1960–1979, and finally 1950–1959.
Type of Receptor Building	The receptor building type affects the blood lead levels of the occupants according to time spent, ceiling height, and cleaning frequency. For children, who spend most of their time either in schools or in residences, the residential and school receptor buildings lead to the largest blood lead changes. For adults, the largest blood lead changes are also observed when the adults are in the residential receptor building, although the difference across building types is more moderate in adults.
Containment Options	Using containment plastic decreases blood lead changes. Vertical plastic decreases blood lead changes at all but the closest receptor building (lower transport) while horizontal plastic decreases blood lead changes at the closest receptor building (lower track-in).

8.2.2. Maximum Hourly Dust

Figure 8-1 summarizes the maximum hourly dust loadings across all the scenarios. The graph provides the percentage of scenarios where the maximum-in-time dust loading in the receptor building exceeded each loading level on the x-axis. These values are the mean, 95th, and 99th percentiles across all iterations in the scenario.

The time is takes loadings to return to background levels is another metric of interest that helps contextualize maximum loading values and their exponential decrease over time. Once routine cleaning starts, the lead dust levels began to decrease exponentially, with 81.6% percent of scenarios returning to background within an average of 6 months after the start of the renovation. Average estimates of time to background dust levels for exterior modeling ranged from 0-93 weeks with an average of 13 weeks.

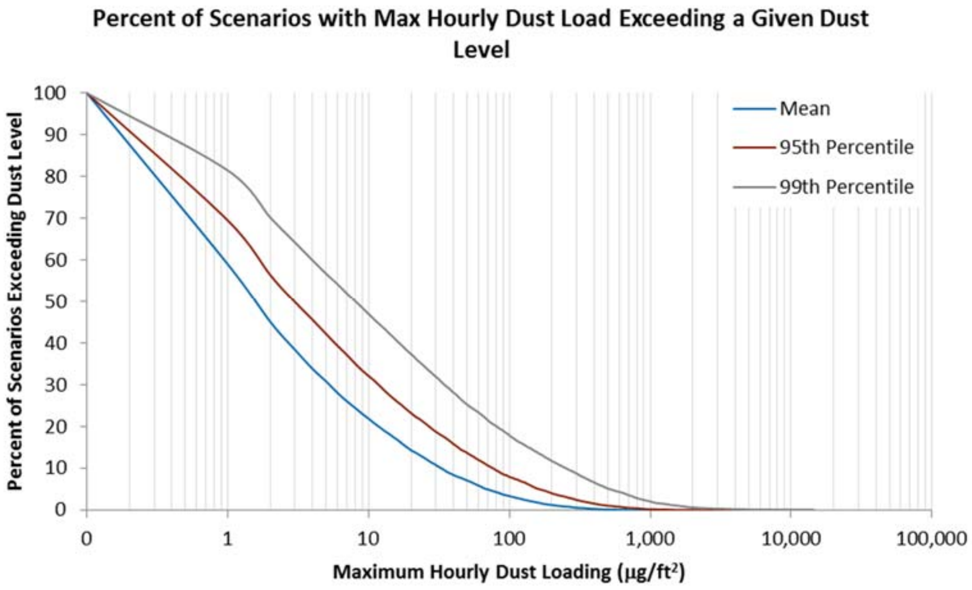


Figure 8-1. Maximum Hourly Dust Distribution for Exteriors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related loadings for buildings across the U.S.

8.2.3. Renovation-Related Blood Lead and Bone Lead

Figures and Tables presented in this section provide information comparing results to various blood lead levels. Blood lead values that are shown (0.1 ug/dl, 1 ug/dl, 10 ug/dl, etc) are for illustrative purposes only and are not intended to evaluate potential hazards due to lead from renovations in P&CBs.

Figure 8-2 provides the percentage of scenarios that exceed each renovation-related blood lead change on the x-axis. The graphs show the mean and 95th percentile blood lead change in children at both 5 months after the renovation and 15 months after the renovation. These time points are examples of outputs generated from distributions from the Monte Carlo results. These distributions can be generated from all of the post-renovation time points (1 month, 5 month, 10 months, 15 months, 20 months, 25 months, 30 months, 40 months, 50 months).

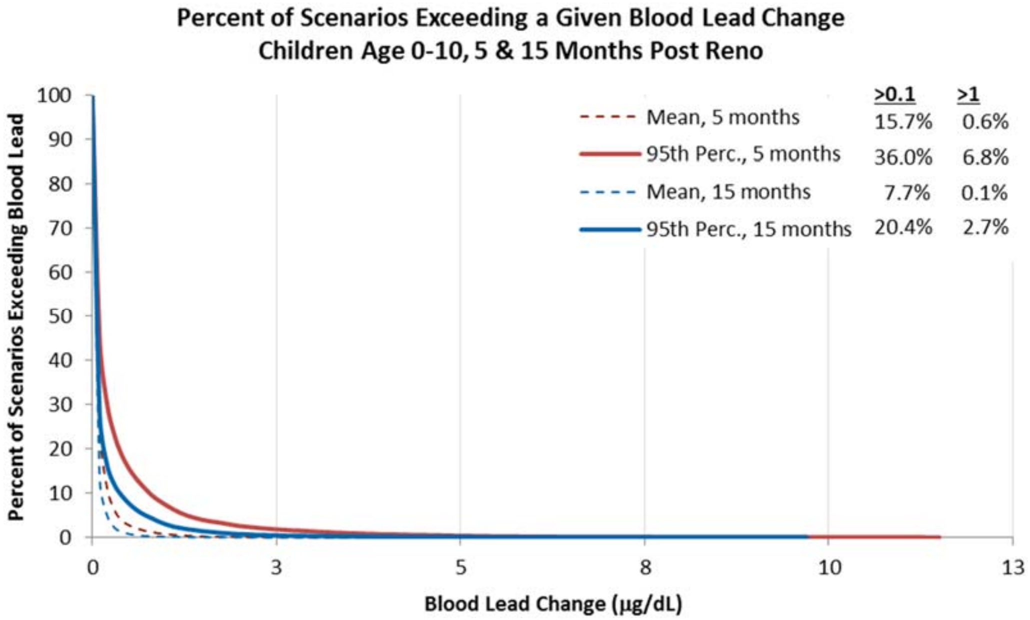


Figure 8-2. Renovation-Related Blood Lead Distribution for Exteriors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related blood lead values for individuals across the U.S.

Table 8-2 provides a summary of the 95th percentile hypothetical blood lead changes across all exterior scenarios for each age group at 1, 5, 20, and 50 months post-renovation. It also provides the lifetime average blood lead statistics (see Section 7.3.1). Table 8.2 shows the percent of scenarios where the 95th percentile renovation-related blood lead model estimates (for hypothetical individuals) exceed various blood lead levels. An additional filter was applied so that only those blood lead values that remained elevated above pre-renovation blood lead values for at least 4 weeks after the start of the renovation are included in Table 8-2. The overall pattern indicated small changes in blood lead levels in most scenarios, with adults experiencing lower blood lead changes than children. Table 8-3 shows the percent of scenarios where either at least 1 percent (100 iterations) or 10 percent (1000 iterations) of the total Monte Carlo iterations (10,000) for that scenario exceeded several example blood lead levels (0.1 ug/dL, 1 ug/dL, and 10 ug/dl, selected for illustrative purposes only).

Table 8-2. Percentage of Exterior Scenarios with 95th Percentile Renovation-Related Blood Lead Change Levels Exceeding Specific Values*

Blood Lead Changes (µg/dL)	Age 0 – 10					Age 18-49					Age 50-80				
	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.
0.1	49.38%	35.99%	16.74%	11.06%	15.32%	47.21%	28.86%	9.05%	6.76%	0.11%	47.21%	28.19%	8.78%	6.89%	0.00%
0.5	22.06%	14.28%	5.68%	3.81%	3.29%	13.61%	2.94%	0.53%	0.53%	0.00%	13.44%	2.57%	0.51%	0.52%	0.00%
1	12.06%	6.83%	1.90%	1.09%	1.00%	6.06%	0.17%	0.05%	0.06%	0.00%	5.76%	0.26%	0.05%	0.05%	0.00%
2	5.03%	2.48%	0.50%	0.33%	0.23%	1.73%	0.00%	0.00%	0.00%	0.00%	1.78%	0.00%	0.00%	0.00%	0.00%
3	2.93%	1.28%	0.23%	0.15%	0.08%	0.63%	0.00%	0.00%	0.00%	0.00%	0.68%	0.00%	0.00%	0.00%	0.00%
4	1.88%	0.66%	0.12%	0.07%	0.03%	0.27%	0.00%	0.00%	0.00%	0.00%	0.35%	0.00%	0.00%	0.00%	0.00%
5	1.29%	0.36%	0.07%	0.04%	0.01%	0.10%	0.00%	0.00%	0.00%	0.00%	0.15%	0.00%	0.00%	0.00%	0.00%
10	0.22%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%
15	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

*Percentages less than 0.01% are rounded to 0%

Table 8-3. Percentage of Exterior Scenarios with Either 1% or 10% of Iteration Blood Lead Changes Exceeding Specific Values*

At Least 1% of Iterations Are Greater than Given Value															
Blood Lead Changes (μg/dL)	Age 0 – 10					Age 18-49					Age 50-80				
	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.
0.1	65.48%	53.64%	31.08%	21.16%	29.80%	49.05%	38.04%	18.93%	13.60%	1.18%	47.88%	36.60%	17.92%	12.89%	0.20%
1	25.59%	18.65%	8.63%	6.36%	6.04%	10.59%	2.78%	0.56%	0.62%	0.00%	10.07%	2.22%	0.51%	0.53%	0.00%
10	1.52%	0.54%	0.10%	0.05%	0.04%	0.10%	0.00%	0.00%	0.00%	0.00%	0.10%	0.00%	0.00%	0.00%	0.00%

At Least 10% of Iterations Are Greater than Given Value															
Blood Lead Changes (μg/dL)	Age 0 – 10					Age 18-49					Age 50-80				
	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.
0.1	39.88%	26.40%	10.76%	7.18%	9.73%	26.29%	12.80%	2.68%	2.24%	0.01%	24.70%	11.57%	2.30%	1.88%	0.00%
1	6.79%	3.26%	0.64%	0.40%	0.30%	2.20%	0.00%	0.00%	0.00%	0.00%	2.00%	0.03%	0.00%	0.00%	0.00%
10	0.05%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

*Percentages less than 0.01% are rounded to 0%

Figure 8-3 expands on the results in Table 8-2 provides a summary of the 95th percentile hypothetical blood lead changes across all exterior scenarios for each age group at 1, 5, 20, and 50 months post-renovation. It also provides the lifetime average blood lead statistics (see Section 7.3.1). Table 8.2 shows the percent of scenarios where the 95th percentile renovation-related blood lead model estimates (for hypothetical individuals) exceed various blood lead levels. An additional filter was applied so that only those blood lead values that remained elevated above pre-renovation blood lead values for at least 4 weeks after the start of the renovation are included in Table 8-2. The overall pattern indicated small changes in blood lead levels in most scenarios, with adults experiencing lower blood lead changes than children. Table 8-3 shows the percent of scenarios where either at least 1 percent (100 iterations) or 10 percent (1000 iterations) of the total Monte Carlo iterations (10,000) for that scenario exceeded several example blood lead levels (0.1 ug/dL, 1 ug/dL, and 10 ug/dl, selected for illustrative purposes only).

Table 8-2, showing the full distribution of the mean and 95th percentile blood lead changes at three different months post-renovation and for the lifetime average blood lead.

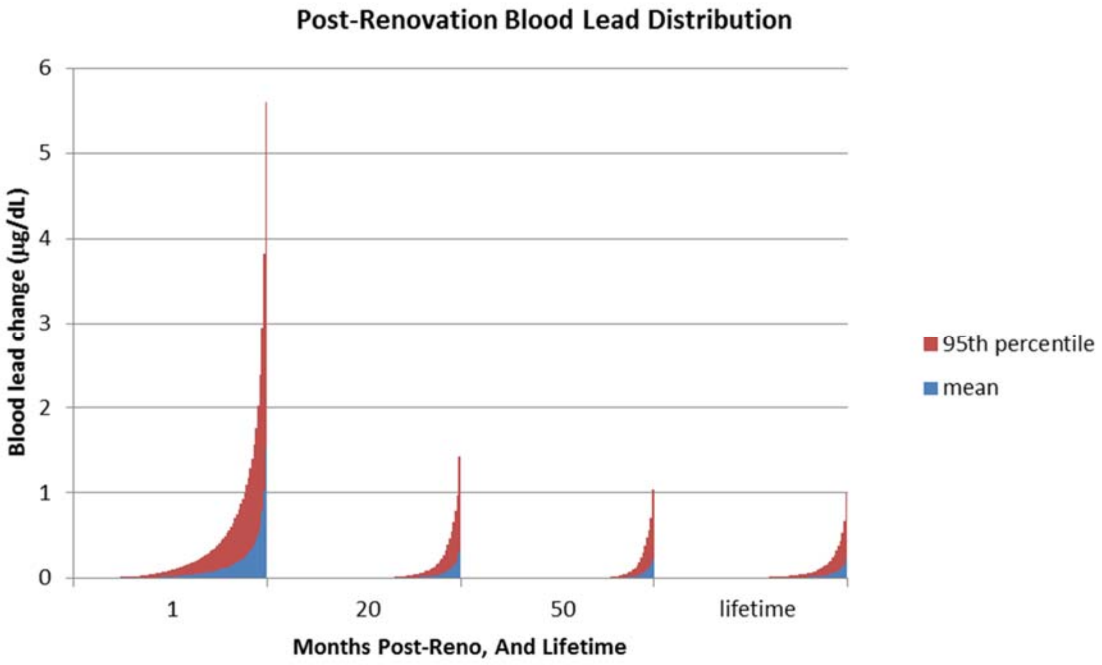


Figure 8-3. Renovation-related Blood Lead Distributions for All Exterior Scenarios

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related blood lead values for individuals across the U.S.

Figure 8-4 shows the percentage of the mean and 95th percentile bone lead changes that exceeded each value on the x-axis for both cortical bone (A) and trabecular bone (B). These values are shown at 50 months post-renovation, which is the maximum time captured in the Approach. Overall, the bone lead changes for most adults was small, less than 0.04 µg/g for cortical bone lead and 0.5 µg/g for trabecular bone lead at the mean and the 95th percentile.

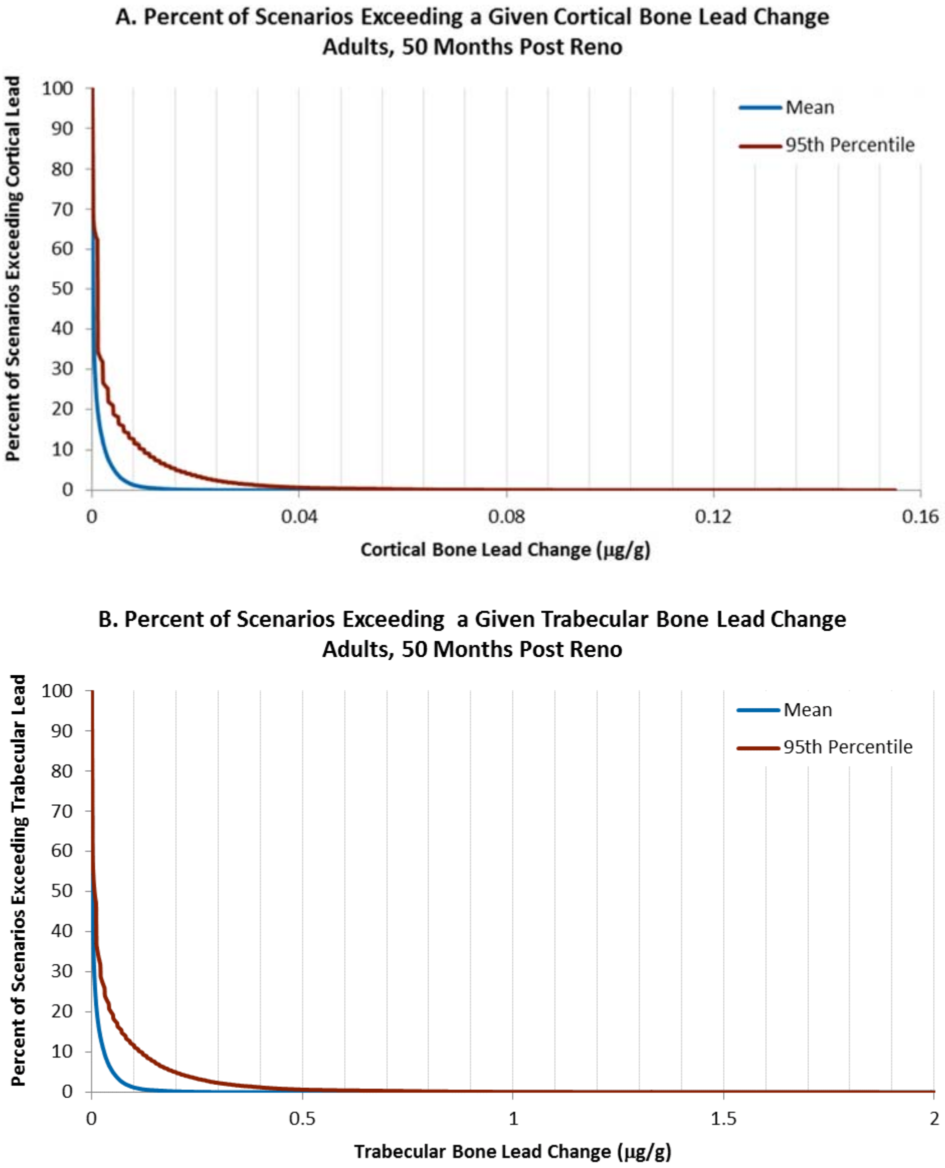


Figure 8-4. Renovation-related Bone Lead Distributions for Exteriors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related bone lead values for individuals across the U.S.

8.2.4. Health Effects

Figure 8-5 shows the percentage of scenarios that exceeded each IQ change value on the x-axis for the mean and 95th percentile scenario results and at both 5 and 15 months post-renovation (panel A) and for the lifetime-average (panel B). Maximum IQ changes were greater than 6 IQ points, but the majority of the mean predictions were less than 1 IQ point. The 95th percentile hypothetical individual, however, experienced at least a 1 IQ point change in 2 percent of the scenarios when examining the lifetime average blood lead.

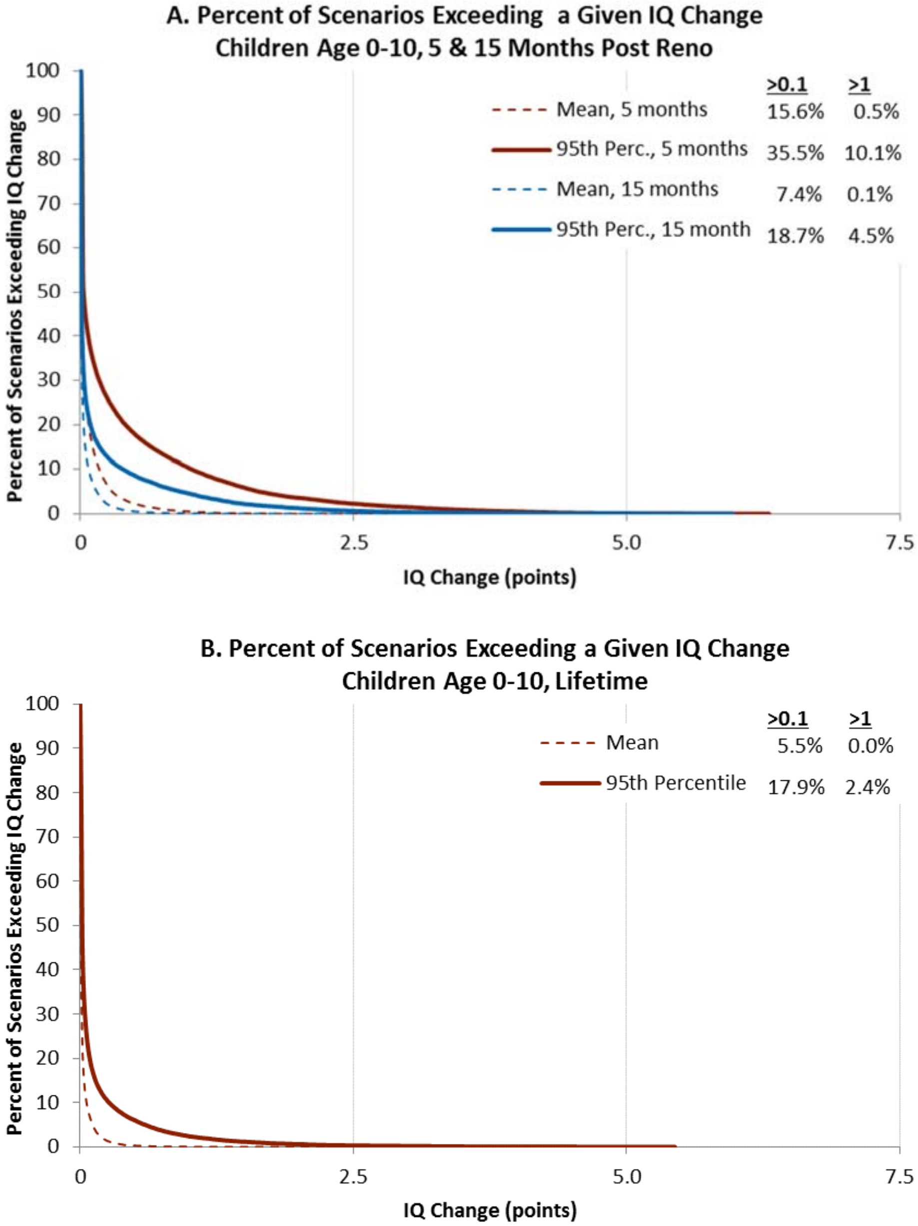


Figure 8-5. Renovation-related IQ Change Distributions for Exteriors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related health effects for individuals across the U.S.

Figure 8-6 provides the percentage of CVDM hazard ratios (panel A), GFR risk ratios (panel B), and birth weight reduction (panel C) that exceeded each value on the x-axis for the mean and the 95th percentile cases. For the CVDM and GFR effects, 5 and 15 months were used while 5 and 10 months were selected for birth weight reduction (to capture different times during pregnancy). The mean hazard or risk ratios for both CVDM and GFR were low for most scenarios, although the 95th percentile reached hazard or risk ratios above 1.10 for a small percentage of scenarios. The birth weight reduction values were low, with the 95th percentile 10-month value exceeding only 5 grams in 1 percent of the scenarios.

Figure 8-6 applies to hypothetical scenarios only. Results do not show distribution of renovation-related health effects for individuals across the U.S.

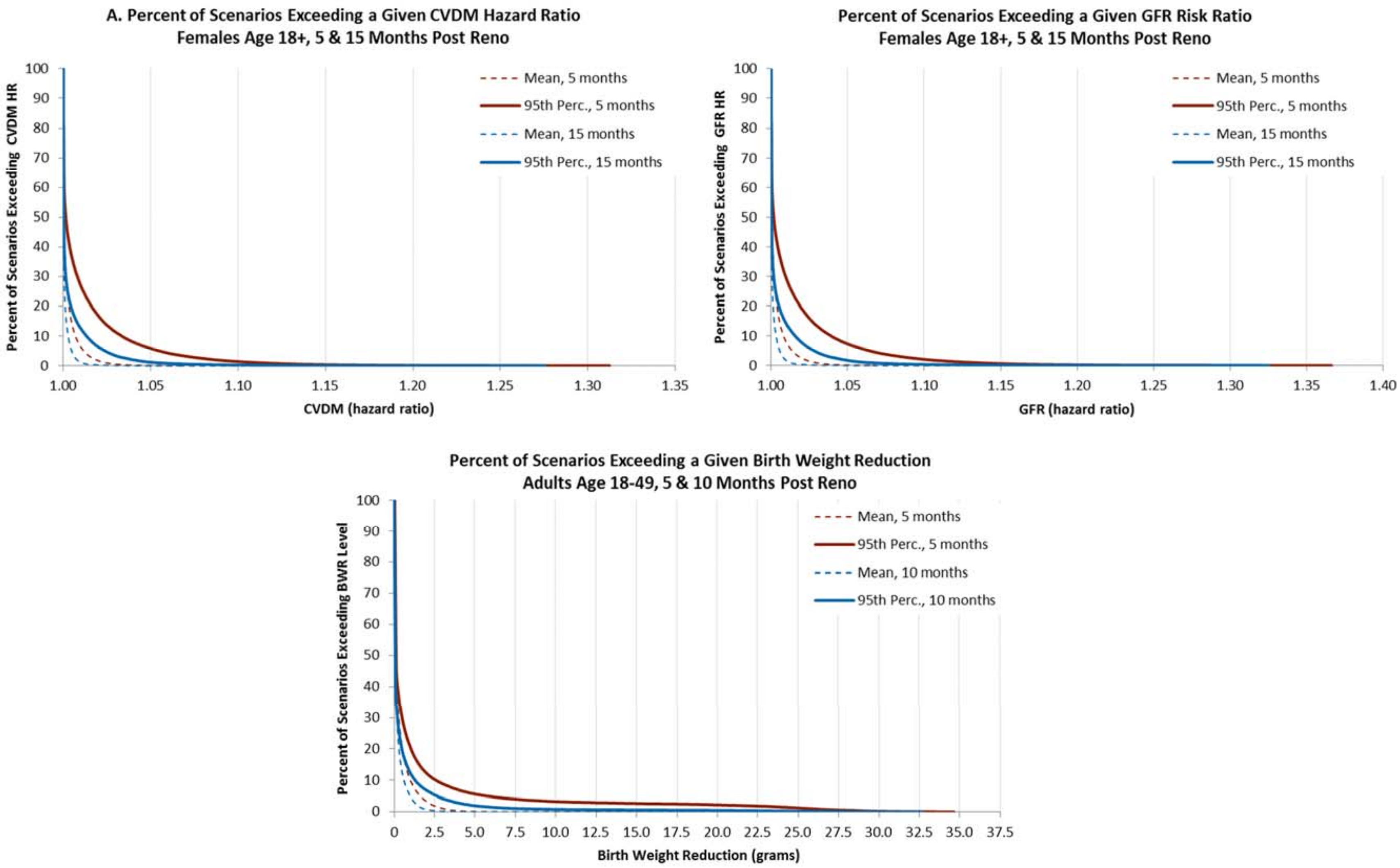


Figure 8-6. Hazard Ratio (A), Risk Ratio (B), and Birth Weight Reduction (C) Distributions for Exteriors

8.3. Sensitivity Analysis for an Exterior Scenario

To assess the sensitivity of the blood lead estimates to the different input variables, several analyses were performed, as follows.

- **Categorical Sensitivity Analysis:** Define a "base case" and vary one or two variables at a time to determine the trends in the blood lead results. This analysis was performed for variables that are "categories" rather than continuous numerical distributions (e.g., building type and building vintage).
- **Numerical Sensitivity Analysis:** Define a "base case" and vary each variable value by 5 percent and 50 percent to determine the percentage change in the blood lead results. The 5 percent change analysis represents a "local" sensitivity analysis; the small change in the input variables illustrates how small changes in the current values would affect the model predictions. The 50 percent change analysis represents a "global" sensitivity analysis; the large change in the input variables illustrates how model predictions would vary over a broader range of input value assumptions. This analysis was performed for variables that are either point estimates or continuous distributions (e.g., air exchange rate and the amount of lead in the paint) (US EPA 2001).

This section describes the results from each of the analyses.

8.3.1. Categorical Sensitivity Analysis

For the categorical analysis, two types of categorical variables are addressed in the Approach: scenario variables and sampled variables. These were treated separately in the sensitivity analysis. For the scenario variables, the "base case" was defined by choosing the scenario variable values as shown in Table 8-4. This case was chosen because it would result in relatively high blood lead changes but would not be the "worst-case" scenario. Then, a series of additional scenarios was defined by changing one or two scenario variables at a time. These cases were then run with 10,000 iterations and the renovation-related blood lead changes were compared.

Table 8-4. Categorical Scenario Variables Included in Exterior Sensitivity Analysis

Categorical Sensitivity Case	Receptor Building Type	Receptor Location	Control Option	Renovation Activity	Vintage	Size
Base	Commercial	50 ft	None	Power sanding	Pre1930	Medium (F2T2)
Residential	**Residential**	50 ft	None	Power sanding	Pre1930	Medium (F2T2)
Agricultural	**Agricultural**	50 ft	None	Power sanding	Pre1930	Medium (F2T2)
Industrial	**Industrial**	50 ft	None	Power sanding	Pre1930	Medium (F2T2)
School	**School**	50 ft	None	Power sanding	Pre1930	Medium (F2T2)
0 ft	Commercial	**0 ft**	None	Power sanding	Pre1930	Medium (F2T2)
300 ft	Commercial	**300 ft**	None	Power sanding	Pre1930	Medium (F2T2)
800 ft	Commercial	**800 ft**	None	Power sanding	Pre1930	Medium (F2T2)
With plastic, 50 ft	Commercial	50 ft	**Plastic**	Power sanding	Pre1930	Medium (F2T2)
With plastic, 0 ft	Commercial	**0 ft**	**Plastic**	Power sanding	Pre1930	Medium (F2T2)
Trim, 800 ft	Commercial	**800 ft**	None	**Trim Replacement**	Pre1930	Medium (F2T2)
Trim 0 ft	Commercial	**0 ft**	None	**Trim Replacement**	Pre1930	Medium (F2T2)
Later Vintage	Commercial	50 ft	None	Power sanding	**1960-1979**	Medium (F2T2)
Small Building	Commercial	50 ft	None	Power sanding	Pre1930	**Small (F1T1)**
Big Building	Commercial	50 ft	None	Power sanding	Pre1930	**Large (F3T3)**

Figure 8-7 shows the trends across the different sensitivity analysis cases for the categorical scenario variables. Overall, the trends matched the direction of the trends in the input variables and reflected those presented in

Table 8-1. The renovation-related blood lead change tended to decrease with distance from the renovated building, with the implementation of plastic control options, and for lower-emitting activities. Changes in blood lead due to the renovation also tended to be smaller for adults than for children, although this trend was also affected by the amount of time each age group spends in the receptor building. For children, the largest blood lead changes were observed in residences where the children spend much of their time. For adults, individuals in residences continued to have higher blood lead changes, but the change across the receptor building types was smaller. For building size, both the smaller and larger buildings led to higher blood lead changes when compared to intermediate sized buildings.

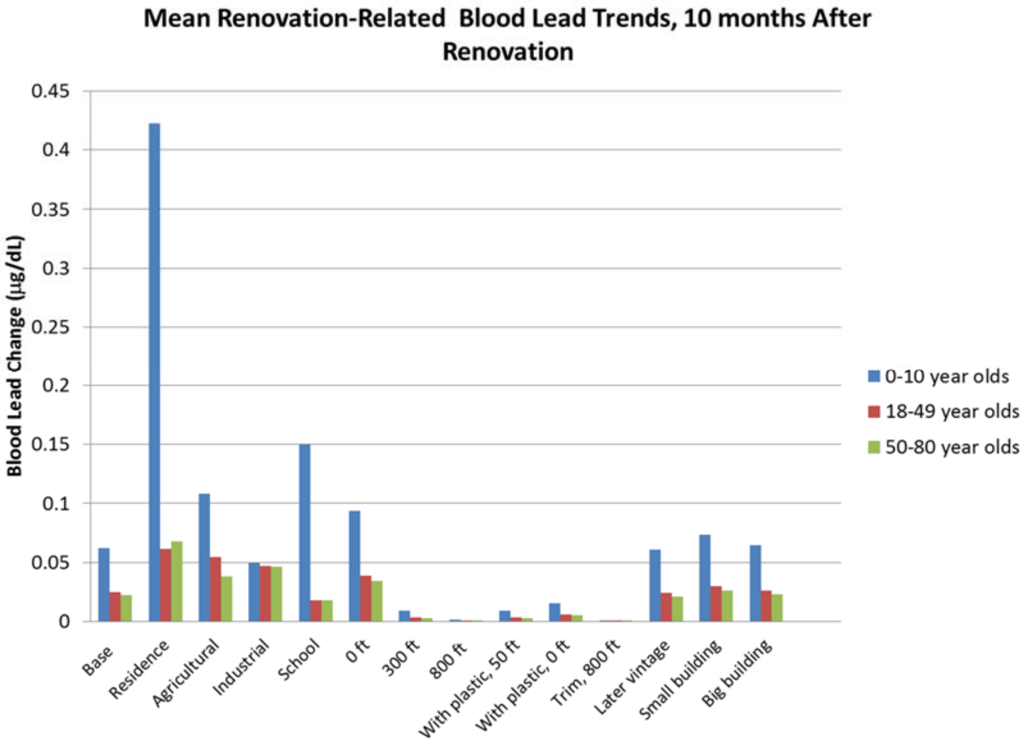


Figure 8-7. Categorical Scenario Variable Sensitivity Analysis Trends, Exteriors

For the Monte Carlo categorical variables, the residential scenario above was selected as the "base" case and the Monte Carlo categorical variables were set to specific values within their distributions. Note that setting the Monte Carlo variables to central tendency values means the residential sensitivity case has a somewhat different value than in Figure 8-7, where the Monte Carlo variables were all sampled. Then, the value of each was changed one at a time, as shown in Table 8-5. The biokinetic variability GSD was also included in this analysis; a value of 1.6 (the Agency default in the IEUBK model) was compared with the Approach value of 1.9.

Table 8-5. Categorical Monte Carlo Variables Included in Exterior Sensitivity Analysis

Monte Carlo Categorical Variable	Base Value	Sensitivity Value
GSD	1.9	1.6
Receptor Vintage	Pre-1930	1960–1979
Receptor Height	1 Story	3 Stories
Percent Carpet	Hard Surface	Carpet
Cleaning Frequency	Once a Week	Once a Month
Age (years)	2, 35, and 65	10, 18, and 50
Time Spent (fraction)	Median	95th Percentile

Figure 8-8 shows the trends across the Monte Carlo categorical variable sensitivity analysis cases. For this scenario, the GSD chosen (either 1.9 or 1.6) had a relatively limited effect on the mean blood lead changes. The receptor building vintage and cleaning frequency led to large changes for children; for the vintage, the later vintage had a lower background lead dust value, so cleaning to achieve background value after the renovation took much longer. For this reason, children were exposed to renovation lead longer and had a higher blood lead change (even though their absolute blood lead including background was lower than a child in an older vintage residence). Blood lead changes tended to decrease with the height of receptor building in this scenario, where the receptor building was assumed to be 50 ft from the renovated building. At greater heights, the winds are stronger, so the lead dust spread farther and faster, leading to lower dust levels at close receptor buildings and higher dust levels at greater distances. Changing the ages from near the center of the age bins (2, 35, 65) to the edge of the bin (10, 18, 50) tended to lead to decreases in the renovation-related blood lead changes. Finally, increasing the time spent percentile tended to increase the blood lead changes; in this scenario, the changes were relatively modest because children already spend a large amount of time in residences in the median time spent case (the base cases here in the sensitivity analysis). The relative change was larger for children in other receptor building types. Representative values for time spent were chosen for the sensitivity analysis. See Appendix L for a discussion of how time spent was estimated for the Approach.

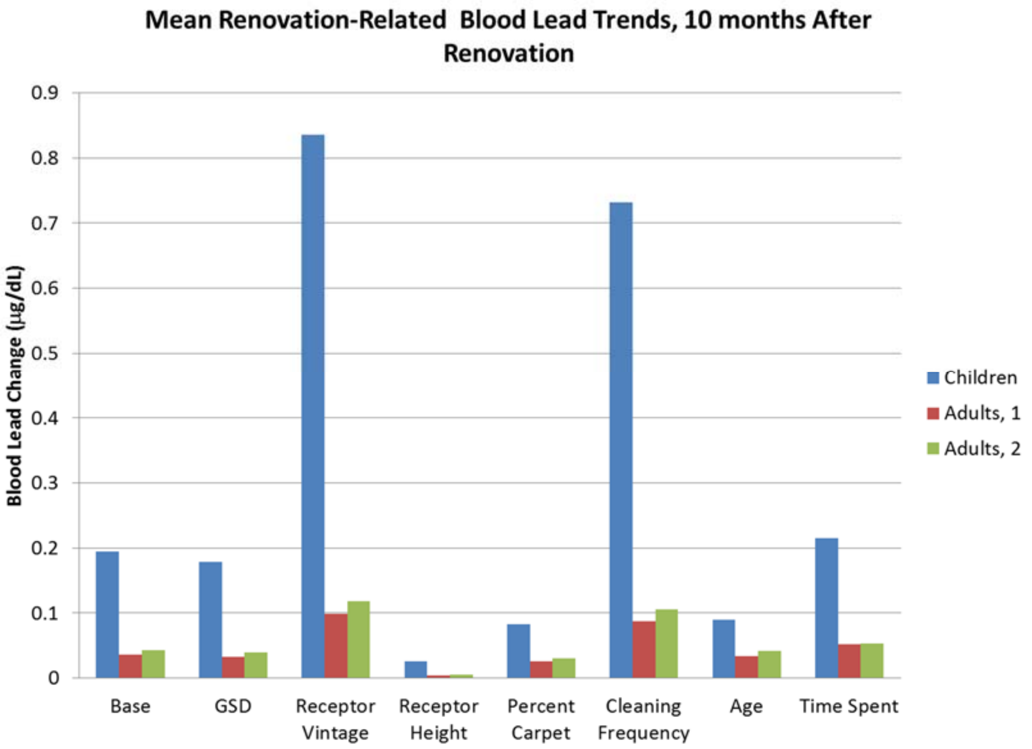


Figure 8-8. Categorical Monte Carlo Variable Sensitivity Analysis Trends for Exteriors

8.3.2. Numerical Sensitivity Analysis

As discussed above in the introduction to Section 8.4, the numerical sensitivity analysis included variables that were either point estimates or continuous distributions in the Approach. Each value was increased by both 5 percent and 50 percent to perform both a local and global sensitivity analysis. The exception is the lead dust penetration factor, which is set to 1 in the Approach; this value was decreased by 5 percent and 95 percent instead because the value cannot exceed 1. The variables included in the analysis are shown in Table 8-6.

Table 8-6. Numerical Variables Included in Exterior Sensitivity Analysis

Variable	Base Value (Mean or Point Estimate)	50% Value	5% Value
Lead in Paint (XRF) (g/cm^2)	0.0107	0.0160	0.0112
Obstruction Adjustment Factor	1	1.5	1.05
Aerosol Emission Fraction	0.112	0.168	0.118
Dust Model Penetration	1	0.5	0.95
Dust Model Deposition (hr^{-1})	0.65	0.98	0.68
Background Dust Loading (µg/ft^2)	13.4	20.1	14.1

Variable	Base Value (Mean or Point Estimate)	50% Value	5% Value
Air Exchange Rate (hr^{-1})	0.63	0.95	0.66
Dust Model Resuspension (hr^{-1})	0.00014	0.00021	0.00015
Soil Density (g/m^3)	2600000	3900000	2730000
Track in Soil Depth (m)	0.015	0.023	0.016
Track in Rain Efficiency	0.50	0.75	0.53
Track in Hard Surface Depth (m)	0.0010	0.0015	0.0011
Particulate Track-in Rate (g/day)	0.93	1.40	0.98
Soil Porosity	0.20	0.30	0.21
Receptor Building Volume (m^3)	508	762	533
MatFrac	0.13	0.20	0.14

After performing each simulation with 10,000 iterations, two key metrics were estimated:

- **Elasticity:** The percent change in the renovation-related blood lead divided by the percent change in the input variable. Elasticity is a measure of the percent change in the result for each percent change in the input variable.

- **Sensitivity score:** Elasticity multiplied by the coefficient of variation (CV) of the variable. The sensitivity score incorporates information about the spread in the distribution for a given variable. Variables that have high elasticities (indicating high sensitivity) but that have relatively tight distributions (low CVs) will not exert as strong an influence over the outcome as a variable with a moderate elasticity but very wide distribution.

Table 8-7 shows the elasticities for each age group for both the 50 percent and 5 percent sensitivity cases, where the rows have been sorted to indicate the variables with the highest elasticity magnitudes at the top of the table. Positive elasticities indicate the variable is positively correlated with the renovation-related blood lead, while negative elasticities indicate the variables are negatively correlated. The analysis indicates that the amount of lead in the paint on the renovated building, the obstruction adjustment factor, the fraction of removed paint that is aerosolized, the dust model penetration, the dust model deposition rate, and the background dust loading had the highest elasticities. Both the lead in the paint and the obstruction adjustment elasticities indicated that for every 1 percent change in these variables, the renovation-related blood lead values for children change by approximately 0.3 percent; elasticities tended to be much lower for adults.

Table 8-7. Elasticities for the Numerical Variables in the Exterior Sensitivity Analysis

Variable	50%			5%		
	Age 2	Age 35	Age 65	Age 2	Age 35	Age 65
Lead in Paint (XRF) (g/cm^2)	0.314	0.050	0.059	0.285	0.046	0.055
Obstruction Adjustment Factor	0.314	0.050	0.059	0.285	0.046	0.055
Aerosol Emission Fraction	0.314	0.050	0.059	0.285	0.046	0.055
Dust Model Penetration	0.161	0.015	0.018	0.203	0.020	0.024
Dust Model Deposition (hr^{-1})	0.109	0.011	0.013	0.119	0.012	0.014
Background Dust Loading (μg/ft^2)	-0.095	-0.010	-0.011	-0.150	-0.015	-0.018
Air Exchange Rate (hr^{-1})	0.069	0.007	0.008	0.084	0.008	0.010
Dust Model Resuspension (hr^{-1})	-0.031	-0.003	-0.004	-0.036	-0.004	-0.005
Soil Density (g/m^3)	-0.008	-0.001	-0.001	-0.011	-0.001	-0.001
Track in Soil Depth (m)	-0.005	-4.6E-04	-0.001	-0.007	-0.001	-0.001
Track in Rain Efficiency	-0.004	-3.5E-04	-4.1E-04	-0.006	-0.001	-0.001
Track in Hard Surface Depth (m)	-0.003	-2.8E-04	-3.3E-04	-0.004	-3.6E-04	-4.4E-04
Particulate Track-in Rate (g/day)	0.002	2.4E-04	2.9E-04	0.002	2.2E-04	3.0E-04
Soil Porosity	0.002	1.9E-04	2.3E-04	0.002	1.7E-04	1.8E-04
Receptor Building Volume (m^3)	-0.002	-1.7E-04	-2.0E-04	-0.002	-2.2E-04	-2.3E-04
MatFrac	0.000	-3.6E-05	-3.6E-05	0.000	-3.6E-05	-5.2E-05

These trends are depicted graphically in Figure 8-9. Where possible (i.e., where a distribution for the variable could be estimated), the sensitivity scores are also shown in the figure. The sensitivity scores indicate that when the spread in the distributions were taken into account, the relative sensitivity of the background dust loadings increased. Without knowledge of the accurate shape of the distribution of all variables or estimates of the predicted error in each variable prediction, however, interpretation of the sensitivity scores is difficult.

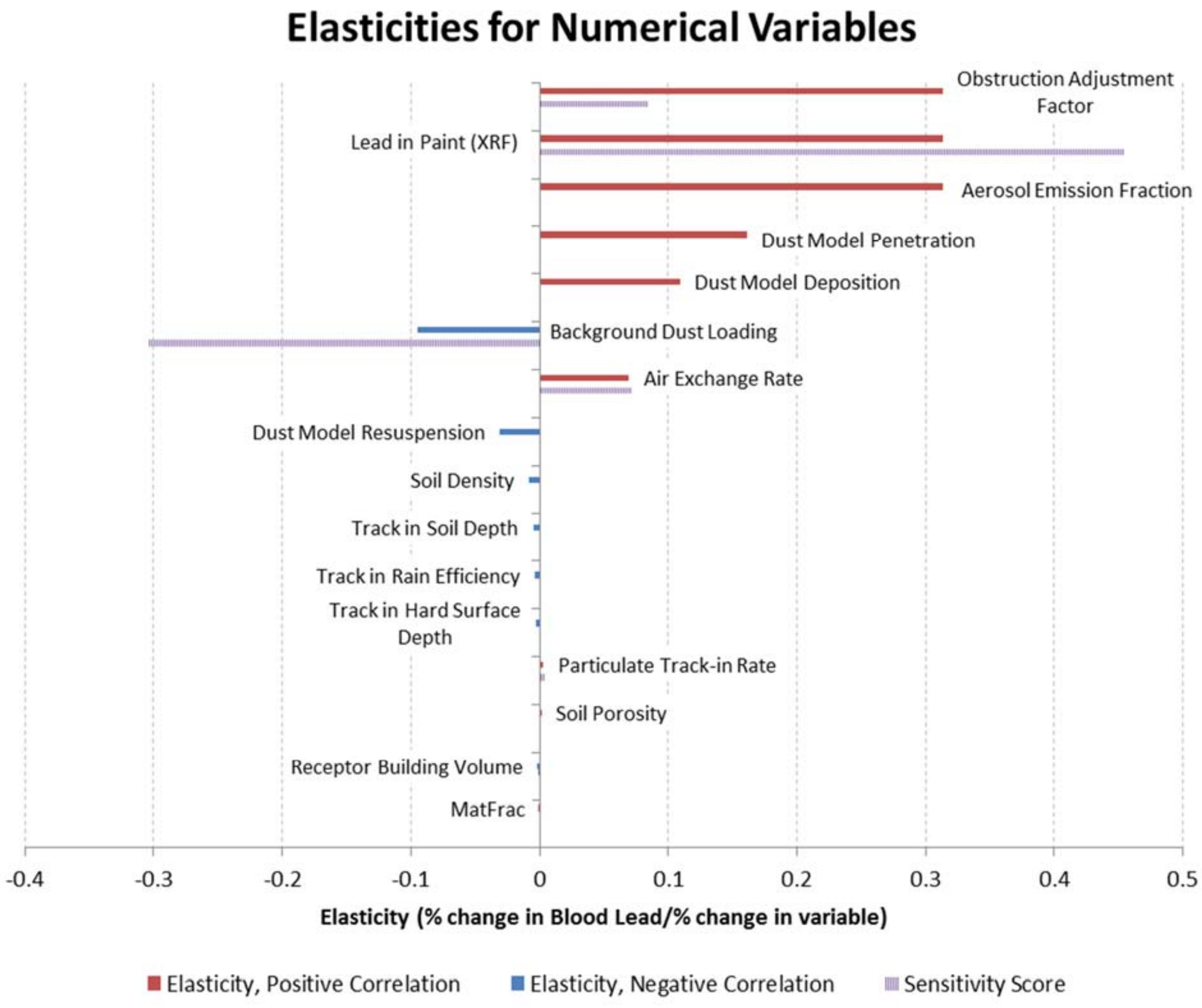


Figure 8-9. Numerical Variable Elasticities and Sensitivity Scores (Where Available), Exterior Analysis

8.4. Summary of Results for Interior Monte Carlo Scenarios

This section summarizes the interior scenario results from the millions of iterations that were modeled to characterize renovation-related changes in blood lead concentrations and incremental health effect changes for children and adults. This section provides some insight into the overall magnitude and distribution of results and the trends in results across different scenario variables.

Throughout this section, blood lead concentrations and IQ changes are presented to one decimal point (i.e., overall resolution of 0.1 μg/dL blood lead and 0.1 IQ points). Hazard or risk ratios are presented to the nearest 0.01 and birth weight is presented to the nearest 0.1 gram. This level of resolution was selected to be consistent with the modeling capabilities. Results are summarized in this section in various ways: a percentile (average, 95th) for a specific incremental environmental media, blood lead, or health effect within a scenario, comparisons of the percent of scenarios across all scenarios that went above a value, and comparison of iterations within a scenario that went above a value.

For all graphs and charts shown throughout Section 8, it is important to reiterate that the results apply only to the exposure scenarios as described for purposes of the Approach. These results do not show the estimated proportion of building types with an estimated media concentration or the estimated proportion of the US population that is predicted to experience the specific blood lead change or incremental health effect. This is because the scenarios have not yet been evaluated to determine how likely or unlikely they are to occur with respect to current work-practices and renovation activities within P&CBs.

Nine unique time-at-blood-measurement values (e.g. 1 month, 5 month, 10 months, etc) were chosen and combinations of these are shown in the charts for health effects for relative comparison. There is uncertainty about how long a person would need to be exposed to elicit a response. In many cases in the interior analysis, the 1-month post-renovation blood lead and health effect estimates were very high and exceeded the levels presented in the health effects papers themselves. EPA chose not to restrict application of the IQ, CVDM, and eGFR equations to a particular blood lead threshold, because these equations are parameterized with respect to the ratio of renovation blood lead and background blood lead.

EPA will evaluate all time-at-measurement values in the context of the exposure scenario, but the 1-month post-renovation estimates are likely not biologically feasible. The blood lead and health effect changes should be considered in context. Blood lead levels remained elevated, especially during the renovation, but quickly decreased over time. A high short-term increase in blood lead could lead to an effect later in life but whether that effect would be attributable to the high short-term exposure or lifetime exposure at varying background levels is unknown. In addition, before making a hazard determination, EPA will put upper-percentile exposures into context using the frequency of occurrence of each scenario and each percentile in the scenario.

8.4.1. Trends Across Scenario Variables

Table 8-19 provides a summary of trends observed in the interior analysis across the different scenario variables. Additional graphical representation of these trends is provided in Section 8.5.1.

Table 8-8. Summary of Interior Trends Analysis

Trend Category	Trends Observed
Loadings during Dust Generation	Increases in the loadings during the dust-generating phase and the rest-of-renovation phase cause the renovation-related blood lead changes to increase. In general, the dust generating phase and rest-of-renovation loadings are correlated, since higher dust-generating loadings will correspond with high rest-of-renovation loadings. The relative effect of the two loadings will depend in part on the durations of the two phases, with changes in longer duration phases having a larger impact than changes to shorter duration phases.
Loadings during Rest of Renovation	
Duration of Dust Generation	The duration of the dust-generating affect blood lead levels because lead loadings increase with the duration of renovation activities. The duration of the rest of renovation also affects blood lead levels because lead loadings can remain elevated through the rest of renovation phase. As these durations increase, the associated blood lead changes increase as well. These values also tend to be correlated because the rest-of-renovation duration is estimated using a multiplier applied to the dust-generating duration.
Duration of Rest of Renovation	
Carpet vs. Not-carpet	In general, carpeting tends to decrease the overall blood lead changes compared with hard floors. This trend is related to the cleaning efficiency; in the Approach, the minimum carpet cleaning efficiency is higher than the minimum hard floor cleaning efficiency. Thus, for cleaning episodes beyond about 4 or 5 cleanings, each carpet cleaning episode is more efficient and the lead dust levels return to background faster than with hard floors. Looking across the scenarios, identical scenarios without carpet tend to be 1.6 higher than the carpeted scenarios on average when comparing the 10 month post-renovation blood lead changes in children. The ratio increases for increasing months post-renovation.
Type of Renovated Building	The building type impacts the blood lead changes primarily via the effect of time-spent in the building. Children's largest average time-spent is in schools, so the school building type gives the largest blood lead changes for children age 0-10. Adults spend the most time on average in Building Category 1 (Office, outpatient healthcare, and public order/safety), so this building type gives the largest adult blood lead changes, with adults 18-49 having higher changes than adults 50-80. The type of building also impacts the cleaning frequencies, with food service/retail, schools, and hospitals/lodging being cleaned more frequently on average than offices and warehouses. This tends to decrease the overall blood lead changes in the buildings that are cleaned more frequently. Thus, in children, there is a competing effect in schools between more frequent cleaning versus more time spent in the building.
Room Size	Room size has two competing effects on the indoor dust levels: increased wall surface area leads to greater lead emission while increased floor space leads to a greater area over which to spread the lead dust (dilution). Overall, increasing the room size while maintaining the same ceiling height will tend decrease the blood lead change (dilution effect wins out).
Job Intensity/ Layers of Paint Removed	Both the job intensity and layers of paint removed affect the amount of lead released into the room, so increasing either one increases the overall blood lead change.

8.4.2. Maximum Hourly Dust

Figure 8-10 summarizes the dust-generating and rest-of-renovation loadings across all scenarios. The graph provides the percentage of all scenarios in each loading bin. Some individuals were exposed to elevated lead loadings throughout the renovation while other individuals were exposed beginning with the routine cleaning phase. For the dust-generating phase loadings at <10 ug/ft^2, most of the values that are 0 ug/ft^2 and those reflect the scenarios where the person is not exposed during the dust-generating phase. The loadings just after the dust generating-phase (blue bars) tended to be high, with 92 percent of scenarios having loadings above 1,000 μg/ft^2. The loadings during the rest or renovation phase (red bars) remained elevated but decrease, with 69 percent of scenarios having loadings above 1,000 μg/ft^2. The time it takes loadings to return to background levels is another metric of interest that helps contextualize maximum loading values and their exponential decrease over time. Once routine cleaning starts, the lead dust levels began to decrease exponentially, with 5.1% percent of scenarios returning to background within an average of 6 months. Average estimates of time to background dust levels for interior modeling ranged from 0 to 30 months with an average of 18 months.

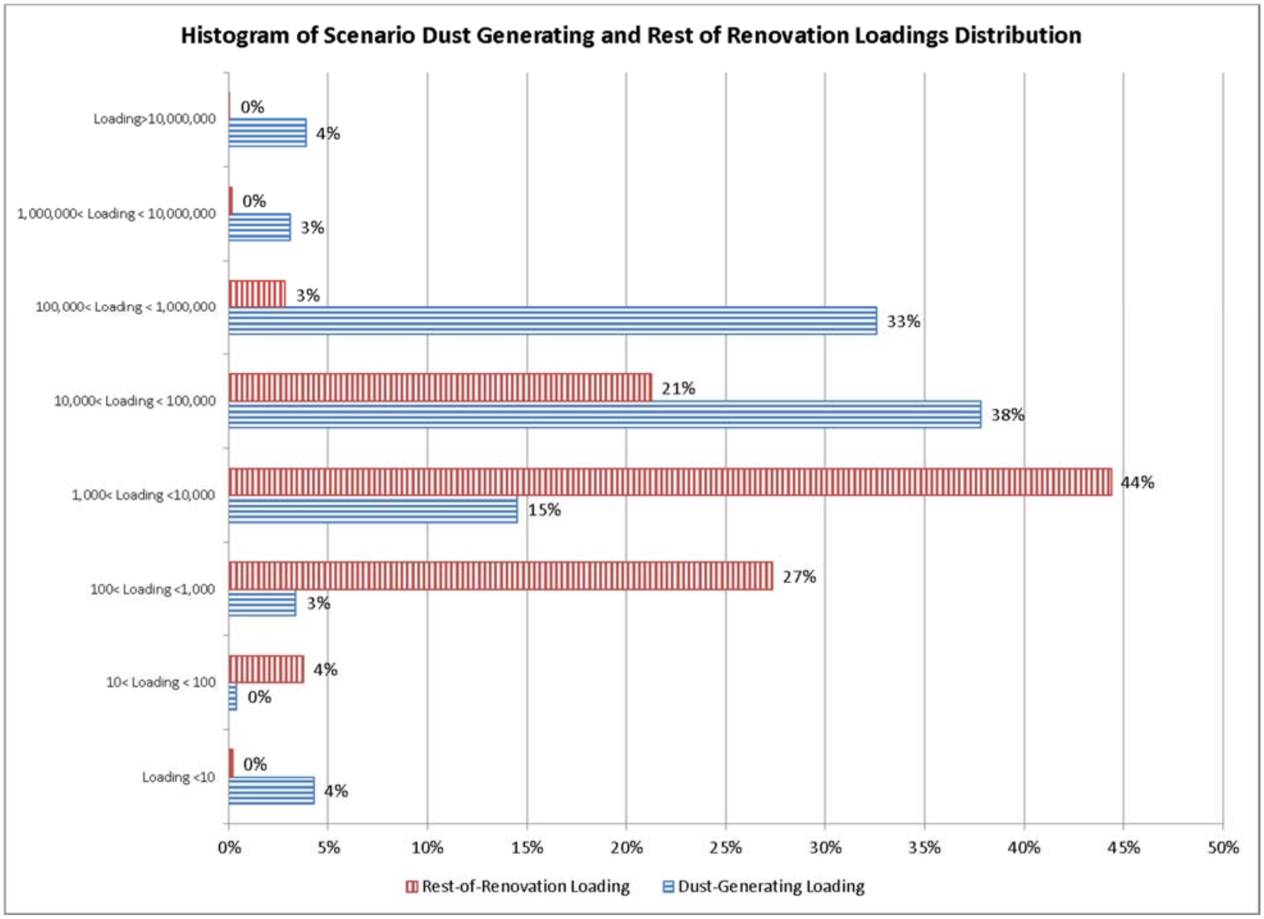


Figure 8-10. Histogram of Scenario Dust-Generating and Rest-of-Renovation Loading Distribution for Interiors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related loadings for buildings across the U.S.

8.4.3. Renovation-Related Blood Lead and Bone Lead

Figures and Tables presented in this section provide information comparing results to various blood lead levels. Blood lead values that are shown (0.1 ug/dl, 1 ug/dl, 10 ug/dl, etc) are for illustrative purposes only and are not intended to evaluate potential hazards due to lead from renovations in P&CBs.

Figure 8-11 provides the percentage of scenarios that exceed each renovation-related blood lead change on the x-axis. The graph plots the mean and 95th percentile blood lead change in children at both 5 months after the renovation and 15 months after the renovation. Overall, the blood lead changes were larger than in the exterior analysis. These time points are examples of outputs generated from distributions from the Monte Carlo results. These distributions can be generated from all of the post-renovation time points (1 month, 5 month, 10 months, 15 months, 20 months, 25 months, 30 months, 40 months, 50 months).

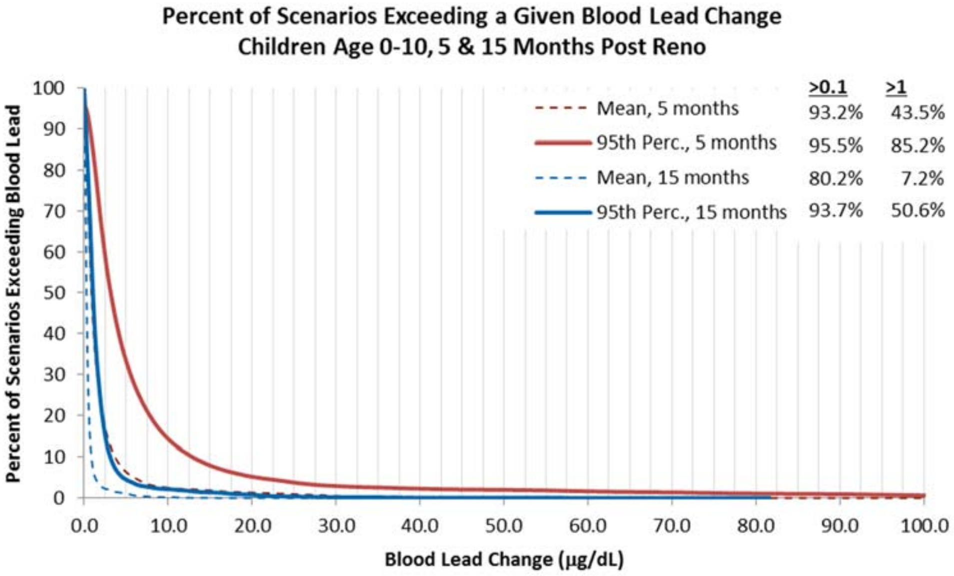


Figure 8-11. Renovation-related Blood Lead Distribution for Interiors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related blood lead values for individuals across the U.S.

Table 8-9 provides an additional summary of the 95th percentile blood lead changes for each age group at 1, 5, 20, and 50 months post-renovation. It also provides the lifetime average blood lead statistics (see 7.3.1 for description of how lifetime blood lead was estimated). At 1 month post-renovation, the 95th percentile blood lead changes were very high. Because the post-renovation time period is defined from the beginning of the renovation, however, some renovations were still ongoing at the 1-month mark. As with interiors, adults had lower estimated blood lead changes than children. Examining the results for lifetime average blood lead change for children, the 95th percentile exceeded 1 μg/dL in about 38 percent of the scenarios.

Table 8-10 shows the percent of scenarios where at least 1 percent (30 iterations) or 10 percent (300 iterations) of the 3,000 interior Monte Carlo iterations exceeded several example blood lead levels (0.1 ug/dL, 1 ug/dL, and 10 ug/dl, selected for illustrative purposes only).

Table 8-9. Percentage of Interior Scenarios with 95th Percentile Renovation-Related Blood Lead Change Levels Exceeding Specific Values*

Blood Lead Changes (µg/dL)	Age 0 – 10					Age 18-49					Age 50-80				
	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.
0.1	95.67%	95.49%	91.20%	64.62%	92.87%	95.52%	93.67%	66.43%	9.05%	15.96%	95.38%	92.36%	57.77%	6.46%	4.59%
0.5	95.24%	92.23%	63.60%	9.89%	64.03%	91.37%	70.86%	4.46%	0.90%	2.76%	88.57%	61.25%	3.57%	0.47%	0.80%
1.0	93.97%	85.17%	32.83%	2.85%	38.40%	83.06%	42.33%	2.06%	0.01%	1.18%	78.04%	33.22%	1.32%	0.01%	0.12%
2.0	89.48%	66.82%	10.29%	1.31%	17.04%	67.72%	17.56%	0.29%	0.00%	0.05%	60.43%	13.07%	0.19%	0.00%	0.00%
3.0	83.83%	51.60%	4.88%	0.51%	9.18%	55.19%	9.82%	0.03%	0.00%	0.00%	46.18%	7.26%	0.02%	0.00%	0.00%
4.0	78.30%	40.82%	3.31%	0.26%	5.84%	44.87%	6.45%	0.01%	0.00%	0.00%	36.40%	4.68%	0.01%	0.00%	0.00%
5.0	73.66%	33.07%	2.61%	0.13%	4.31%	36.86%	4.69%	0.01%	0.00%	0.00%	29.08%	3.45%	0.01%	0.00%	0.00%
10.0	56.34%	14.23%	1.28%	0.00%	2.37%	15.86%	2.03%	0.00%	0.00%	0.00%	11.15%	1.56%	0.00%	0.00%	0.00%
15.0	44.00%	7.87%	0.38%	0.00%	1.94%	8.00%	1.19%	0.00%	0.00%	0.00%	6.47%	0.82%	0.00%	0.00%	0.00%
20.0	35.29%	5.16%	0.16%	0.00%	1.34%	5.33%	0.71%	0.00%	0.00%	0.00%	4.68%	0.36%	0.00%	0.00%	0.00%
30.0	24.00%	2.90%	0.01%	0.00%	0.47%	3.48%	0.16%	0.00%	0.00%	0.00%	3.35%	0.10%	0.00%	0.00%	0.00%
40.0	16.47%	2.25%	0.00%	0.00%	0.14%	3.27%	0.02%	0.00%	0.00%	0.00%	3.21%	0.01%	0.00%	0.00%	0.00%
50.0	11.85%	1.97%	0.00%	0.00%	0.05%	3.13%	0.01%	0.00%	0.00%	0.00%	2.98%	0.00%	0.00%	0.00%	0.00%
75.0	6.44%	1.18%	0.00%	0.00%	0.00%	2.89%	0.00%	0.00%	0.00%	0.00%	1.50%	0.00%	0.00%	0.00%	0.00%
100.0	4.37%	0.61%	0.00%	0.00%	0.00%	1.42%	0.00%	0.00%	0.00%	0.00%	1.32%	0.00%	0.00%	0.00%	0.00%

*Percentages less than 0.01% are rounded to 0%

Table 8-10. Percentage of Interior Scenarios with Either 1% or 10% of Iteration Blood Lead Changes Exceeding Specific Values*

At Least 1% of Iterations Are Greater than Given Value															
Blood Lead Changes (μg/dL)	Age 0 – 10					Age 18-49					Age 50-80				
	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.
0.1	95.70%	95.66%	95.21%	87.26%	95.29%	95.66%	95.38%	88.10%	55.62%	47.59%	95.64%	95.15%	84.64%	50.42%	14.68%
1	95.34%	93.37%	73.79%	18.41%	71.59%	91.72%	75.55%	9.78%	1.06%	2.81%	89.36%	67.11%	6.66%	0.58%	0.94%
10	74.39%	34.84%	2.92%	0.10%	4.86%	37.77%	5.18%	0.02%	0.00%	0.00%	30.49%	3.75%	0.01%	0.00%	0.00%

At Least 10% of Iterations Are Greater than Given Value															
Blood Lead Changes (μg/dL)	Age 0 – 10					Age 18-49					Age 50-80				
	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.	1 mnth	5 mnths	20 mnths	50 mnths	Life.
0.1	95.64%	95.13%	85.12%	38.79%	88.94%	95.26%	95.26%	39.06%	3.51%	7.45%	94.91%	94.91%	27.45%	3.10%	3.35%
1	91.83%	91.83%	15.43%	1.88%	23.55%	74.61%	74.61%	0.79%	0.00%	0.21%	68.07%	68.07%	0.39%	0.00%	0.00%
10	44.05%	44.05%	0.42%	0.00%	1.83%	7.88%	7.88%	0.00%	0.00%	0.00%	6.53%	6.53%	0.00%	0.00%	0.00%

*Percentages less than 0.01% are rounded to 0%

Figure 8-12 expands on the results presented in Table 8-9 to show the full distribution of the mean and 95th percentile blood lead changes at three different months-post-renovation and for the lifetime average blood lead.

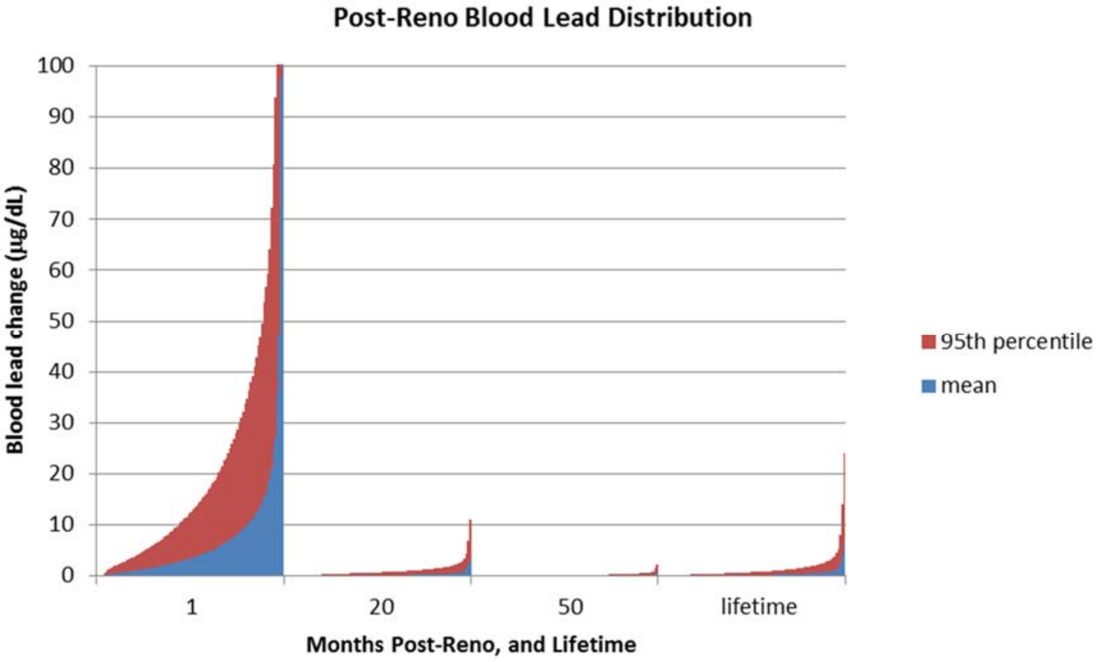


Figure 8-12. Renovation-related Blood Lead Distributions for All Interior Scenarios

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related blood lead values for individuals across the U.S.

Figure 8-13 shows the percentage of the mean and 95th percentile bone lead changes that exceeded each value on the x-axis for both cortical bone (A) and trabecular bone (B). These values are shown at 50 months post-renovation, which is the maximum time captured in the Approach. Overall, the bone lead changes for adults were small, with most scenarios having changes less than 0.5 µg/g for cortical bone lead, and less than 2.5 µg/g for trabecular bone lead at both the mean and 95th percentile.

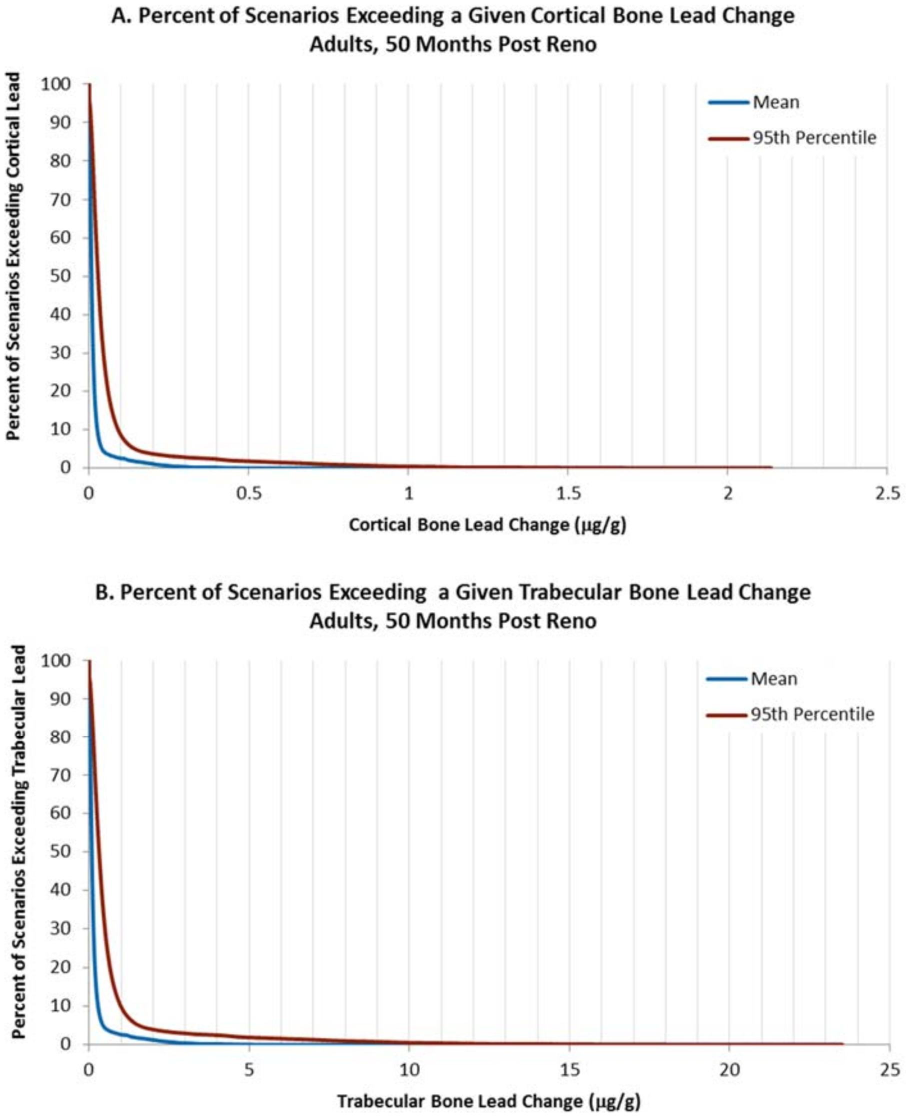


Figure 8-13. Renovation-related Bone Lead Distributions for Interiors

Applies to hypothetical scenarios only. Results do not show distribution of renovation-related bone lead values for individuals across the U.S.

8.4.4. Health Effects

Figure 8-14 shows the percentage of scenarios that exceeded each IQ change value on the x-axis for the mean and 95th percentile scenario results and at both 5 and 15 months post-renovation (panel A) and for the lifetime-average (panel B). The IQ changes in the interior analysis were much larger than in the exterior analysis. In the 95th percentile case at 15 months after the renovation, nearly 65 percent of the scenarios showed a renovation-related IQ change of at least 1 point, whereas in the mean case the percent drops to 6.3.

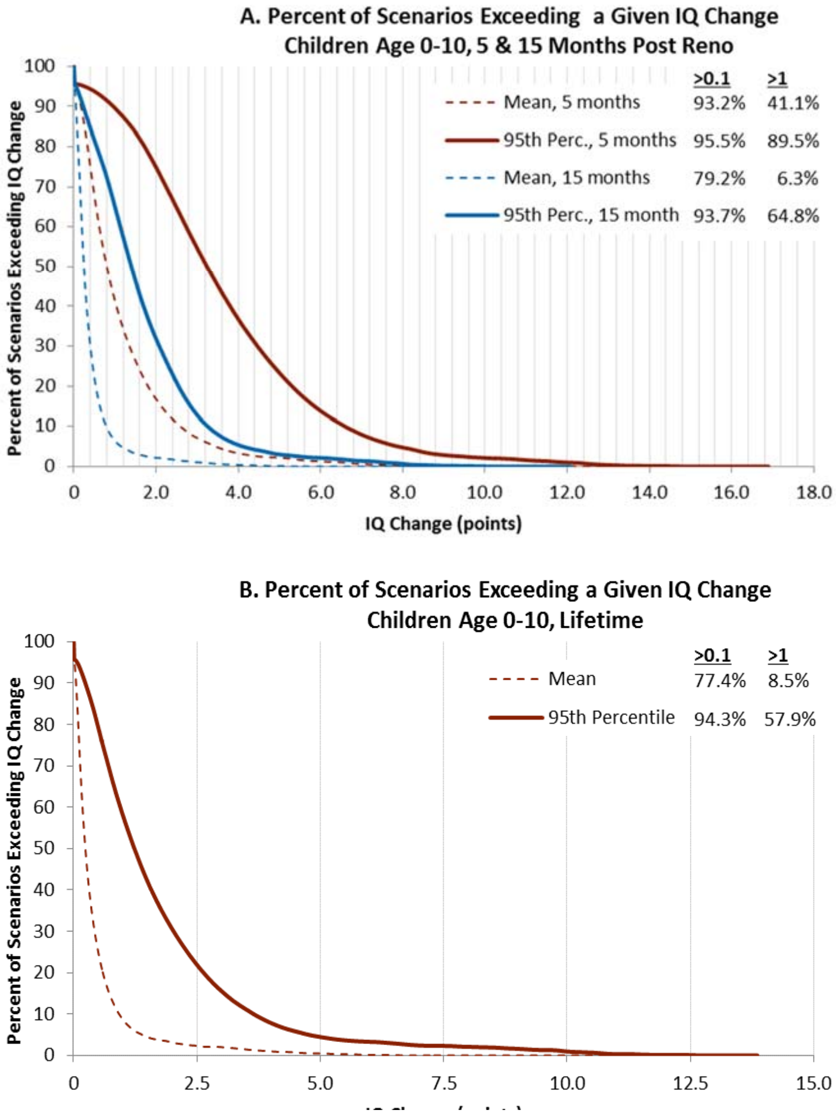


Figure 8-14. Renovation-related IQ Change Distributions for Interiors

Figures 8-14 and 8-15 apply to hypothetical scenarios only. Results do not show distribution of renovation-related health effects for individuals across the U.S.

Figure 8-15 provides the percentage of CVDM hazard ratios (panel A), GFR risk ratios (panel B), and birth weight reduction (panel C) that exceeded each value on the x-axis for the mean and 95th percentile cases. The CVDM and GFR effects were examined at 5 and 15 months, while 10 and 20 months were selected for birth weight reduction (to capture the pregnancy duration and a value 10 months later). The hazard and risk ratios and birth weight reductions estimates were significantly greater than in the exterior analysis.

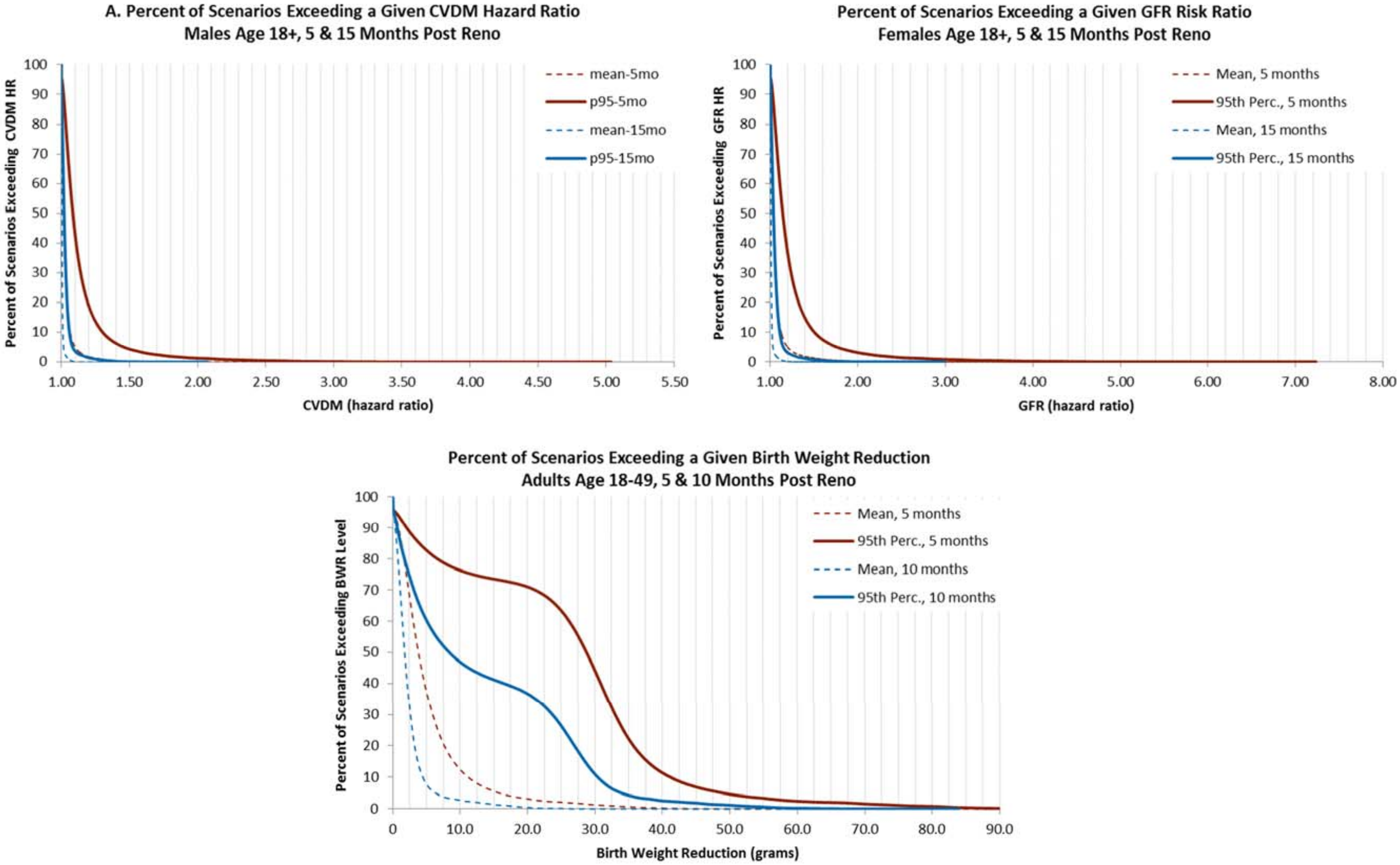


Figure 8-15. Hazard Ratio (A), Risk Ratio (B), and Birth Weight Reduction (C) Distributions for Interiors

8.5. Sensitivity Analysis for an Interior Scenario

Similar to the exterior analysis, sensitivity of the blood lead estimates to the input variables was assessed using both a categorical and a numerical sensitivity analysis, as described in this section. An additional sensitivity analysis was conducted to evaluate the effects of different combinations of the location of the exposed individual, the time that exposure starts, and the amount of time spent in different locations. This analysis is described on its own in Section 8.6.3.

8.5.1. Categorical Sensitivity Analysis

For the categorical analysis, two types of categorical variables are included in the Approach: scenario variables and Monte Carlo variables. These were treated separately in the sensitivity analysis. For the scenario variables, the "base case" was defined by choosing the scenario variable values as shown in Table 8-11. Then, a series of additional scenarios were defined by changing one or two scenario variables at a time. These cases were then run with 3,000 iterations and the renovation-related blood lead changes were compared.

Table 8-11. Scenario Categorical Variables Included in Interior Sensitivity Analysis

Categorical Sensitivity Case	Building Type	Carpet Type	Allowed/Not Allowed	During-Loading (μg/ft^2)	Post-Loading (μg/ft^2)	During-duration (weeks)	Post-duration (weeks)
Base	Office	No	Allowed	15000	350	2	1
Supermarket	**Supermarket**	No	Allowed	15000	350	2	1
Retail	**Retail**	No	Allowed	15000	350	2	1
School	**School**	No	Allowed	15000	350	2	1
Lodging	**Lodging**	No	Allowed	15000	350	2	1
Not Allowed	Office	No	**Not Allowed**	15000	350	2	1
Low Loadings	Office	No	Allowed	**225**	**66**	2	1
Low Loadings, Not Allowed	Office	No	**Not Allowed**	**0**	**66**	2	1
High Loadings	Office	No	Allowed	**200000**	**1050**	2	1
Long During Duration	Office	No	Allowed	15000	350	**20**	1
Long Post Duration	Office	No	Allowed	15000	350	2	**20**
Long Both Durations	Office	No	Allowed	15000	350	**29**	**29**
With Carpet	Office	**Yes**	Allowed	15000	350	2	1

Figure 8-16 shows the trends across the sensitivity analysis cases for the scenario categorical variables. Overall, the renovation-related blood lead change tended to decrease when the individual was not allowed in the workspace, when the loadings the individual was exposed to were lower, and when the renovation durations were shorter. Trends across the building types reflected differences in the cleaning frequencies and in the time spent in the building for the different age groups, schools representing the highest childhood exposure building type, and offices (“base”) representing the highest adult exposure building type. Also, in the loading range selected for this base case, individuals in the buildings with carpet tended to have lower exposures than those in buildings with hard surface flooring owing to differences in the cleaning efficiencies.

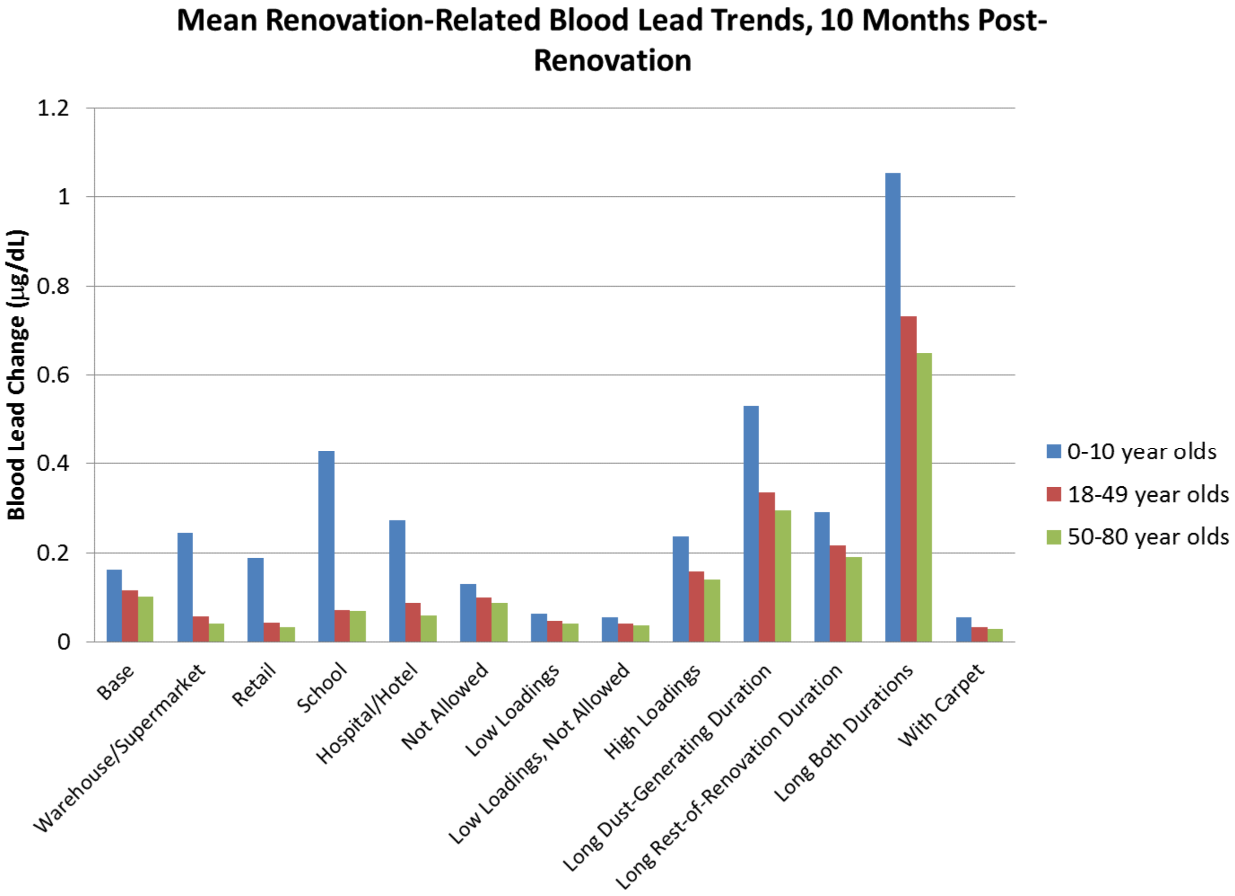


Figure 8-16. Categorical Scenario Variable Sensitivity Analysis Trends, Interiors

For the Monte Carlo categorical variables, the office scenario above was selected as “base” case and the Monte Carlo categorical variables were set to specific values within their distributions. Note that this change means the office base case had a somewhat different value than in Figure 8-16, where the Monte Carlo variables were all sampled. Then, the value of each was changed one at a time, as shown in Table 8-12. The biokinetic variability GSD was also included in this analysis; a value of 1.6 (the Agency default in the IEUBK model) was compared with the Approach value of 1.9.

Table 8-12. Monte Carlo Categorical Variables Included in Interior Sensitivity Analysis

Monte Carlo Categorical Variable	Base Value	Sensitivity Value
GSD	1.9	1.6
Cleaning Frequency	Once a Week	Once a Month
Age	2, 35, and 65	10, 18, and 50
Time Spent	Median	95th Percentile

Figure 8-17 shows the trends across the sensitivity analysis cases for the various Monte Carlo categorical variables. The cleaning frequency and time spent in the building tended to increase the blood lead significantly, while the age and biokinetic GSD had only a modest effect on the mean renovation-related blood lead changes. For time spent, representative values were chosen. See Appendix L for a description for how time spent distributions were estimated for various age groups for the Approach.

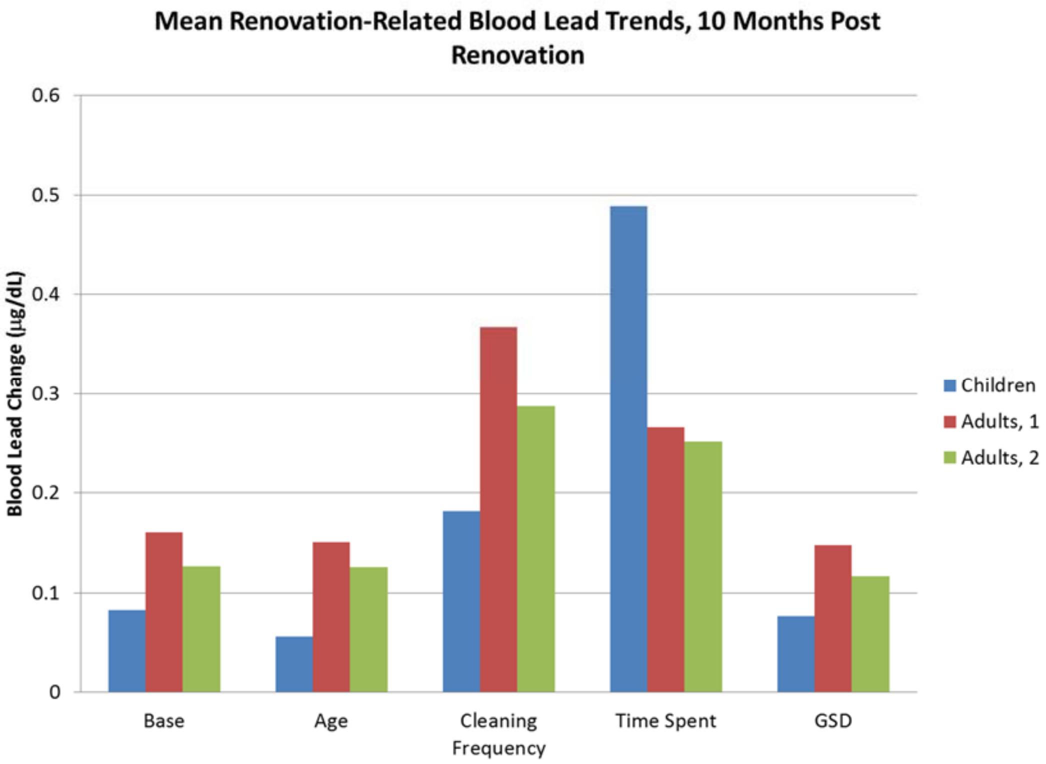


Figure 8-17. Monte Carlo Categorical Variable Sensitivity Analysis Trends, Interiors

8.5.2. Numerical Sensitivity Analysis

As discussed above in the introduction to Section 8.4, the numerical sensitivity analysis included variables that were either point estimates or were continuous distributions in the Approach. Each value was increased by both 5 percent and 50 percent to perform both a local and global sensitivity analysis. The variables included in the analysis are shown in Table 8-13. Only the 5 percent case was simulated for the cleaning factor since it could not be increased above a value of 1. Unlike the dust penetration factor in the exterior analysis, the elasticity was not likely symmetric for this variable with respect to being increased versus decreased; thus, the variable was excluded from the global sensitivity analysis altogether.

Table 8-13. Numerical Variables Included in Interior Sensitivity Analysis

Variable	Base Value (Mean or Point Estimate)	50% Value	5% Value
Base	N/A	N/A	N/A
Job Intensity	0.5	0.75	0.525
Fraction of Paint Removed	0.5	0.75	0.525
Room 1 Size (ft^2)	60	90	63
Room 2 Size (ft^2)	3900	5850	4095
XRF Sampled (g/cm^2)	0.0063	0.0095	0.0066
Ceiling Height (ft)	9	13.4	9.44
Aerosol Emission Fraction	0.0119	0.0179	0.0125
Rate of "Dust Generating" Phase (ft^2/hr)	360	540	378
Rest of Renovation Multiplier	2	3	2.1
Cleaning Factor	0.943	N/A	0.990
Adjacent Factor	0.0057	0.0086	0.0060
Background Dust Loading ($\mu g/ft^2$)	1.22	1.83	1.28

After performing each of these simulations with 10,000 iterations, several key metrics were estimated:

- **Elasticity:** The percent change in the renovation-related blood lead divided by the percent change in the input variable. Elasticity is a measure of the percent change in the result for each percent change in the input variable.

- **Sensitivity score:** Elasticity multiplied by the coefficient of variation (CV) of the variable. The sensitivity score incorporates information about the spread in the distribution for a given variable. Variables that have high elasticities (indicating high sensitivity) but that have relatively tight distributions (low CVs) will not exert as strong an influence over the outcome as a variable with a moderate elasticity but very wide distribution.

Table 8-14 shows the elasticities for each age group for both the 50 percent and 5 percent sensitivity cases, where the rows have been sorted to indicate the variables with the highest elasticity magnitudes at the top of the table. Positive elasticities indicate the variable is positively correlated with the renovation-related blood lead, while negative elasticities indicate the variables are negatively correlated. The analysis indicates the cleaning factor (i.e., the fractional efficiency of the cleaning and other mitigation practices) was the most sensitivity variable with an elasticity of 0.55 (indicating a 0.5 percent change for each 1 percent change in the cleaning factor). Ceiling height, intensity of the job, fraction of paint removed during the job, amount of lead in the paint, and background dust level elasticities indicated the blood lead estimates are moderately sensitive to these variable values.

Table 8-14. Elasticities for the Numerical Variables in the Interior Sensitivity Analysis

Variable	50%			5%		
	Age 2	Age 35	Age 65	Age 2	Age 35	Age 65
Cleaning Factor	N/A	N/A	N/A	–0.553	–0.572	–0.571
Ceiling Height	0.089	0.089	0.089	0.011	0.011	0.011
Intensity (Fraction of Walls Affected)	0.089	0.089	0.088	0.011	0.011	0.011
Fraction of Paint Removed	0.089	0.089	0.088	0.011	0.011	0.011
XRF Sampled	0.082	0.083	0.082	0.011	0.011	0.011
Paint Aerosol Emission Fraction	0.082	0.083	0.082	0.011	0.011	0.011
Background Dust	–0.053	–0.057	–0.057	–0.006	–0.006	–0.006
Room 2 Size	–0.046	–0.046	–0.046	–0.005	–0.005	–0.006
Rate of "Dust Generating" Phase	–0.004	–0.002	–0.002	–1.66E–04	–9.55E–05	–1.05E–04
Adjacent Factor	0.003	0.003	0.002	2.82E–04	2.55E–04	2.36E–04
Room 1 Size	5.00E–04	4.93E–04	4.42E–04	8.56E–05	9.98E–05	8.82E–05

These trends are depicted graphically in Figure 8-18. Where possible (i.e., where a distribution for the variable could be estimated), the sensitivity scores are also shown in the figure. The sensitivity scores indicate that when the spread in the distributions are taken into account, the relative sensitivity of the background dust loadings and the lead in the paint did not change relative to each other. In the absence of knowledge about the accurate shape of the distribution of all variables, however, interpretation of the sensitivity scores is difficult.

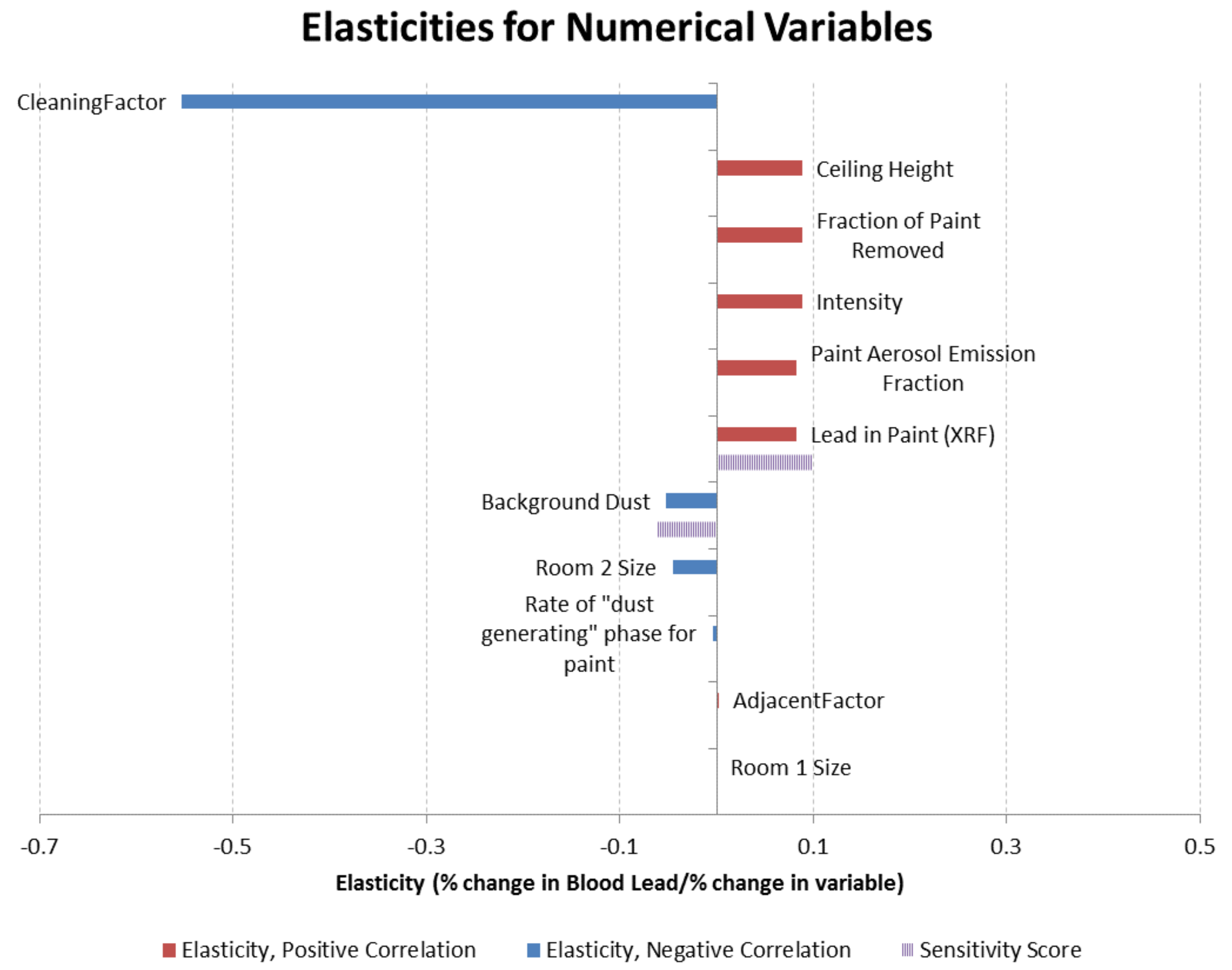


Figure 8-18. Numerical Variable Elasticities and Sensitivity Scores (Where Available), Interior Analysis

8.5.3. Sensitivity to Individual's Location in Time and Space

As discussed in Section 4.2.4, an individual may be located in a number of different rooms in the renovated building, they may be present during the full renovation or for only part of the renovation, and they may either occupy only a single space or multiple spaces within the building during a single visit. The Approach includes scenarios that cover many of these cases, and a sensitivity analysis was conducted to explore the effects of the different assumptions about location and movement through the building.

Error! Not a valid bookmark self-reference. shows the different sensitivity cases run. For this analysis, the work area dust-generating loading were assumed to be 100,000 μg/ft^2; the rest-of-renovation loadings and adjacent room loadings were found by assuming baseline cleaning efficiency and adjacent factors of 0.943 and 0.0057, respectively (see Appendix B). This gave rest-of-renovation loadings of 5,700 μg/ft^{2}and adjacent loadings of 570 μg/ft^2. The "Other Room" loadings were assumed to be 0 mg/ft2. When a person traveled between two different areas, the loadings in the two areas were averaged to give the effective exposure loading (i.e., the person spends half of their time in each room). Finally, the dust-generating and rest-of-renovation durations were both set to 4 weeks. The building type was an office building, where adults have a greater time-spent than children.

Figure 8-18 shows the average renovation-related blood lead for the different age groups for each of the sensitivity cases at 10 months after the start of the renovation. Cases that were included in the Approach are shown in blue and scenarios only included in the sensitivity analysis are shown in red. For the cases run, the cases where the individual is present only during the rest-of-renovation lie roughly in the middle of the cases where they are present for the full renovation and where they are absent for the full renovation. The cases included in the Approach tend to bound the other scenarios, with one exception. Individuals who split their time between an adjacent room and another unaffected part of the building will have lower blood lead changes than those captured in the Approach. Overall, for this particular building, the location of the individual can change the renovation-related blood lead by a factor of 2 or 3.

Table 8-15. Sensitivity Analysis Cases That Explore Effects of Location and Exposure Timing

Case	Number of Building Locations	Room	Present during dust-generation?	Present during rest of renovation?	Present during routine cleaning?
Case 1. One Location, Work Area, Always Allowed in Room During Renovation	One Location	Work Area	Yes	Yes	Yes
Case 2. One Location, Work Area, Partially Allowed in Room During Renovation	One Location	Work Area	No	Yes	Yes
Case 3. One Location, Work Room, Always Allowed in Room During Renovation	One Location	Work Room	Yes	Yes	Yes
Case 4. One Location, Work Room, Partially Allowed in Room During Renovation	One Location	Work Room	No	Yes	Yes
Case 5. One Location, Work Area, Not Allowed in Room During Renovation	One Location	Work Area/Work Room	No	No	Yes
Case 6. One Location, Adjacent Room, Always Allowed in Room During Renovation	One Location	Adjacent Room	Yes	Yes	Yes
Case 7. One Location, Adjacent Room, Partially Allowed in Room During Renovation	One Location	Adjacent Room	No	Yes	Yes
Case 8. One Location, Adjacent Room, Not Allowed in Room During Renovation	One Location	Adjacent Room	No	No	Yes
Case 9. One Location, Other Room	One Location	Other Room	No	No	No
Case 10. 50% work, 50% adjacent, always allowed	Multiple Locations	Work and Adjacent	No	Yes	Yes
Case 11. 50% work, 50% adjacent, partially allowed	Multiple Locations	Work and Adjacent	No	No	Yes
Case 12. 50% work, 50% adjacent, not allowed	Multiple Locations	Work and Adjacent	No	No	No
Case 13. 50% work, 50% other, always allowed	Multiple Locations	Work and Other	No	Yes	Yes
Case 14. 50% work, 50% other, partially allowed	Multiple Locations	Work and Other	No	No	Yes
Case 15. 50% work, 50% other, not allowed	Multiple Locations	Work and Other	No	No	No
Case 16. 50% adjacent, 50% other, always allowed	Multiple Locations	Adjacent and Other	No	Yes	Yes
Case 17. 50% adjacent, 50% other, partially allowed	Multiple Locations	Adjacent and Other	No	No	Yes
Case 18. 50% adjacent, 50% other, not allowed	Multiple Locations	Adjacent and Other	No	No	No

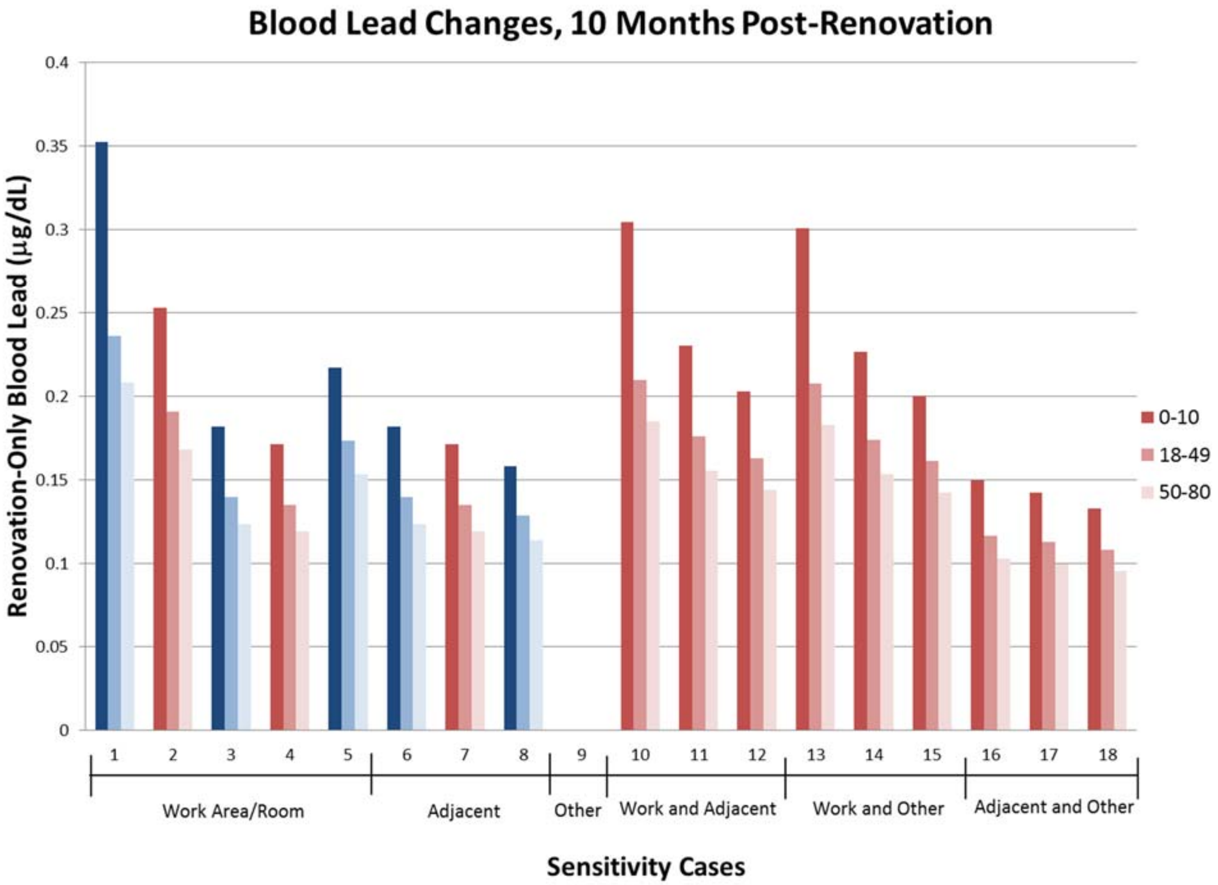


Figure 8-19. Location Sensitivity Analysis Results
Blue bars are cases included in the Approach while red bars are part of the sensitivity analysis only.

9. Uncertainties in the Model Approach

The Approach and the resulting health effect predictions are subject to several uncertainties related to input parameters, models, and equations used to estimate the media concentrations, blood concentrations, and health effects. This section discusses these uncertainties qualitatively, building on results from the sensitivity analysis to focus on key variables.

In general, quantifying the uncertainty or predicting whether the uncertainty represents a low or high bias in the simulated health effects is not possible. For every variable considered in this analysis, care was taken to ensure that the selected values and approaches were neither overly conservative nor likely to bias the results low. Instead, the focus was on finding values and distributions that represent the variability in the U.S. population as a whole. Thus, any biases discovered were corrected, and the direction of the remaining uncertainty cannot be predicted.

9.1. Input Variables

Any model-based approach is limited by the availability and quality of its input data. The Approach described here is data-intensive, and thus, understanding the limitations and uncertainties associated with the input data and assumptions is critical. In addition, any uncertainties and limitations of the data will be propagated throughout the remainder of the downstream calculations and thus can have implications for several different parts of the Approach.

9.1.1. The Dust Study and Estimation of the Emission Rates and Fraction Emitted

The EPA Dust Study (US EPA 2007a) represents the most complete study of lead loading related to interior and exterior renovation activities. The study included several different renovation activities and assessed the effect of various control options on the post-renovation loading. The primary shortcoming of this dataset is the relatively small sample size for each activity/control option combination. In addition, the residences and schools had different job sizes, paint lead content, and contractor crews, making comparison across control options and activities more difficult. Jobs were at times performed on metal railings, wood ceilings, or other room components that might be difficult to compare to other substrates. To account for the differences in job sizes and paint content, the Dust Study loadings were all processed so that the emission rates for exteriors and the fraction emitted for interiors were estimated based on the total particulate loading (rather than the dust loading) that was from a unit area on the wall (see Appendices H and I).

Because not every possible descriptive metric was recorded in the Dust Study, however, some data required for the analysis was estimated in other ways. For example, detailed samples that fully describe the shape of the distribution of dust along the wall were not available. But samples that were taken were mapped and used for estimating emission rates and fraction emitted. For the bulk material fraction, the Approach assumes that the bulk material would fall (within 1 or 2 feet of the job wall) to adjust the sample masses, but this assumption introduces uncertainty in the emission rates.

Data for calculating lead dust emissions from the partial demolition of a building are also limited. The study selected evaluated loadings after the demolition of a block of row houses. The overall emissions were scaled to a per-square-foot-demolished basis to be applied to a single wall of a renovated building in the Approach. The extent to which applying data from a complete demolition to a partial demolition might introduce bias to the results, however, is not possible.

Extrapolation of loadings in P&CBs from the fraction emitted metric derived from the dust study covered a wide range across dust-generation and rest of renovation phases ranging from very low to very high. The upper range of potential loading values present after a renovation, derived from wipe samples or from converted air sampling, has not been well characterized. For interior experiments, the Dust Study only performed the job on a portion of the room. This was usually a small (e.g., 10 to 30 ft^2) patch of wall or ceiling. Because the full room was not renovated, it is difficult to interpret our Approach loading values within the context of the loadings found in the Dust Study. It is plausible that an upper bound floor loading value may exist, but this data gap introduces uncertainty into the analysis.

The Approach estimates the fraction of lead emitted during a renovation activity and is intended to be the best possible estimate given the data available. The values were similar to the single available emission fraction in the literature. Hence, the emission fractions represent an uncertainty in the Approach results. The effect of this uncertainty (to either lower or raise incremental blood lead changes) cannot be quantitatively assessed due to lack of data on actual emission fractions from renovation activities.

9.1.2. Cleaning Frequency and Cleaning Efficiency

The modeled dust loadings in both the exterior and interior analysis are highly sensitive to both the cleaning frequency and cleaning efficiency. Thorough literature searches were conducted for both variables, but only limited data were available. In addition, the frequency and efficiency of cleaning likely vary widely across the different building types and individual buildings. For this reason, these variables introduce uncertainty in the Approach results. The effect of this uncertainty (to either lower or raise incremental blood lead changes) cannot be quantitatively assessed.

9.1.3. Effect of Building Obstructions

In an urban environment, numerous buildings might lie between the renovated building and the downwind receptor building. The effect of these obstructions was incorporated in the Approach by simulating a number of obstruction scenarios in AERMOD using the AERMOD PRIME software. Based on these test runs, a distribution of obstruction adjustment factors was created. To truly capture the infinite combinations of building positions and orientations, however, is not possible. Thus, the obstruction adjustment introduces additional uncertainty in the Approach and the effect of the potential bias cannot be determined.

9.1.4. Frequency and Duration of Renovation Activities

Although information on the frequency of individual renovation activities is available, data on the frequency of these activities in relationship to one another and across specific building types are limited. A given building could experience multiple renovations, ranging from smaller to bigger jobs, over the course of several years. Making assumptions about how often a person in a P&CB would be exposed to multiple renovations over time would have introduced significant uncertainty due to lack of available information. To partially account for this, many different combinations of multiple renovation activities were modeled, but they were assumed to occur at the same time rather than at specified intervals.

9.1.5. Time Spent and Location of the Exposed Individual

The amount of time spent in the renovated P&CB is a highly sensitive variable in the Approach. The CHAD database provides a robust source of data to estimate the distribution of time spent in the various building types. The Approach applies the time spent as a continuous pattern of entering the same building, however, rather than attempting to estimate entry into different buildings of the same type. For certain types of buildings, such as schools and offices, certain individuals are likely to enter only one school or one office per day. For other types of buildings, such as retail buildings, certain individuals are likely to enter different buildings of the same type on a given day. Given the complexity of human activity patterns, accounting for the full range of variability is not possible. The length of time spent between various microenvironments was analyzed, and this metric could be used to help differentiate whether an individual spent time in one building and re-entered that same building (short time-between), or if an individual spent time at different buildings (longer time-between). Thus, the time-spent variable was applied in the same way for all exposed individuals, but has greater or lesser uncertainty in the Approach depending on the type of building and the exposed individual.

In the interior analysis, exposure could start at many different times and occur at different locations. Exposure could start at the beginning of the dust-generating phase, the beginning of the rest-of-renovation phase, or the beginning of the routine-cleaning phase. Individuals also could be located in the work area, in the work room, or in an adjacent room at any of these times. Individuals also could either move between these spaces or remain in one space for the duration of estimated time spent. Some, but not all, of these combinations have been explored in the Approach and the interior sensitivity analysis. Based on what has been explored to date, this variable is highly sensitive, which could be explored further, as it directly influences how long and at what levels individuals are exposed.

9.2. Modeling Approaches

The modeling equations and tools in the Approach were selected with a focus on scientific rigor, peer-review status, and parsimony between the available detail in the input data and the detail in the model equations. In cases where uncertainty was large, such as the Leggett model, efforts were made to update the model algorithms to reflect the most up-to-date information in the literature. The application of multiple modeling approaches, however, creates additional uncertainty in the analysis.

9.2.1. Application of AERMOD

AERMOD is a Gaussian dispersion model and was selected to model the dispersion of renovation dust to nearby locations. To fully capture the transport of mass, particularly in urban areas with more and larger buildings, a full microscale, mass-conserving, fluid dynamics model would be needed. The scope of the current Approach, however, did not allow for the creation or application of such a model. In addition, such a model inherently would be highly uncertain due to the effects of small-scale turbulence and the interaction between the windfield and the city buildings, in addition to the challenges associated with developing the required, highly detailed inputs for enough locations to suitably represent the United States. AERMOD was selected as the most appropriate model for the Approach, but it has not been fully validated for receptors very close to the release site and might introduce significant uncertainty to air concentrations predicted at these distances. AERMOD does allow for land surface information (such as roughness introduced by a city landscape) and windfield modifications due to obstructions, however, to be modeled.

Within AERMOD, modeling paint removal from the surface of an exterior wall as a series of point sources, or stacks, with associated exit velocities and temperatures and stack diameters, is not an ideal representation. Of the various options tested, this represented the best application of AERMOD for exterior renovations. This approach could introduce uncertainty, particularly very close to the renovated building.

9.2.2. Loading to Concentration Conversion Equation

The extent of uncertainty associated with using the loading-to-concentration regression model is difficult to estimate precisely. For this Approach, EPA used three data sources, resulting in an increased sample size and overall decrease in the standard error. The three studies, however, used different approaches for gathering loading data (wipe versus vacuum) and were conducted in different sampling periods (years) and different countries. The overall confidence intervals in the empirical equation are wide, indicating a wide spread in the relationship between lead dust loading and concentration. Alternatively, considering the many covariates that could affect dust loading and lead concentration (cleaning frequency, floor type, condition of interior paint, size and lead concentration of ambient air particles, etc.), that the simple dust loading-dust concentration regression has a significant slope and explains over half the variance in the (logarithm of the) data is notable. In addition, the log-log form of the relationship has a physical basis, where the distribution of lead dust concentrations is taken as arising from random multiple dilutions of dust from multiple sources (Ott, 1995). Extrapolation of the relationship outside the range of loadings in the underlying data, however, will introduce additional uncertainty.

9.2.3. Application of Adult Health Effect Equations and the Time Since Renovation

It is recognized that both children and adults spend time in P&CBs, and the Approach should address potential exposures and health impacts to both. However, the application of the existing adult concentration response functions for this Approach introduces uncertainty for the reasons described below.

Regulations related to lead in gasoline and in consumer paint have led to a steady decline in lead exposure since the early 1980s. However, the existing health effects literature for lead exposure in adults is based on cross-sectional studies that examine blood or bone lead at a single time point.

Because of this, a measure of blood lead level taken at the time when the study was conducted could indicate blood lead levels that are much lower than a decade or two earlier in the adult's life. The full life history of lead in the adult's blood cannot be assessed. Thus, the health effect might be correlated with the blood lead at the time of assessment, but this blood lead level might not have a causal relationship with the health effect; instead, it could simply indicate that people with higher-than-average blood lead levels today likely also had higher-than-average blood lead levels in the past, and these past elevated blood lead levels might have been the true cause of the health effect.

In the Approach, a renovation event triggers an elevated blood lead level for a period of weeks to several years before returning to background. To mimic the cross-sectional design of the health effect studies, a single point after the beginning of the renovation is selected as the blood lead measurement and health effect assessment time. The results are highly sensitive, however, to the choice of how long after renovation the blood lead is assessed. In addition, the past peak blood lead is not captured or accounted for in the health effect equation. From a biological standpoint, no susceptibility window (in terms of either length of exposure or timing of exposure) is known for these health effects, so the sampling time cannot be set based on biological considerations. Lifetime average blood lead levels were also used to estimate health effects in the approach; however, because the equations were not originally developed using this metric, interpretation of these health effect estimates are difficult and application of the equations might be inappropriate.

The health effect equations based on bone lead levels in part overcome this limitation. Bone lead more accurately reflects lifetime exposure to lead rather than a single point estimate. As stated earlier in the Approach, however, EPA is modeling effects from the most recent renovation and as such bone lead estimates are an underestimate in situations where individuals have been exposed to more than one renovation over time. Modeling multiple exposures over time might not be feasible given the wide range of possibilities for timing, proximity to, and types of renovation activities within one person's lifetime.

For the above reasons, the adult health effect predictions are highly uncertain. They are included in the Approach because the adult time-spent values are higher than the children time-spent values, and adults might represent a susceptible population for P&CB exposure. Application of the existing adult concentration response functions, however, introduces significant uncertainty in the results.

9.2.4. Lookup-Table Approach

The interior renovation analysis represents a particular challenge because of the number of possible combinations of building use type, building configuration, room size, and occupant location. Even when carefully constraining each variable to a reasonably low number of values, the combinations of scenarios for the interior renovations exceeds 100 million. Such a large number of scenarios cannot be run using available resources. The lookup-table approach enables a smaller number of representative scenarios to be run and then interpolation between the closest two to estimate the health effects. This approach introduces uncertainty into the calculations. Tests were performed on a subset of scenarios to ensure that the predictions were within 5 percent of the true health effect predictions when run through the Monte Carlo model, and in most cases results were well below 5 percent. Nevertheless, the approach could introduce a small low or high bias for some ranges of lead loadings and durations.

9.2.5. Correlated Variables

The Approach does not account for correlations between many of the input variables. For example, the radial selected (primarily upwind or downwind) and the obstruction adjustment might be correlated. Or, the background dust is likely correlated with cleaning frequency in different buildings, whereas the Approach treats these as entirely separate variables. In some cases, efforts could be made to account for correlations; for example, the lead content in the paint on the renovated building is related to the vintage of the building in the Approach. In addition, the amount of time spent in the receptor building is based on the building type. Owing to a lack of information about such correlations and the potential biases possible with mischaracterizing these correlations in other variables, however, the Approach does not attempt to capture correlations between other variables. By not allowing for correlations, however, both the means and the 95th percentiles could be biased either high or low.

9.2.6. Point-Estimate Variables and the Population Distribution

Many of the variables in the Approach are point estimates rather than distributions (sampled variables) or a series of discrete values (scenario variables). In general, these variables are not expected to be the most sensitive variables in the Approach; time spent, cleaning frequency and efficiency, and the lead content of the paint (all highly sensitive variables) are represented as distributions based on the best input data possible. Because not all variables are included as distributions and because of the uncertainty in the distributions that are included, however, the distributions of the resulting health effects and incremental blood lead changes must be interpreted carefully. Because of the intricacy of the Approach and the complicated nature of the overall exposure assessment objective, how closely the modeled results are related to true population distribution is unknown. The Approach presented here is intended to represent the best estimate possible given the input data and modeling approaches available.

9.2.7. Convergence of Upper Percentiles

The Monte Carlo simulations were performed with 10,000 (exteriors) and 3,000 (interiors) iterations to resolve the mean blood lead changes to within ± 5 percent. True model convergence at all percentiles is not possible, and larger uncertainty is associated with the 95th percentile estimates. In general, however, the model was able to resolve the renovation-related changes to within 0.1 μg/dL blood lead, 0.1 IQ points, ORs to the nearest 0.01, and birth weight to the nearest 0.1 gram.

Despite the uncertainties described above, EPA is confident that the approach taken provides reasonable estimates of exposure input values and modeling outputs given the data sources available. Background blood lead modeled results are very closely aligned with current and past U.S. population blood lead levels, as reported by NHANES. Renovation-related blood lead modeled results for most scenarios indicated a modest increase above background blood lead levels, demonstrating a close alignment between the modeled values and empirical values. The model estimates for the upper percentiles were less certain, just as upper percentile empirical data in NHANES is less certain, but still corresponded to the same general magnitude. This high level of correspondence between complicated multistep modeling and empirical blood lead levels in the current U.S. population is evidence that the many uncertainties in the analysis are likely not introducing specific overall bias for mid-range percentiles.

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